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IN-SITU COAL GASIFICATION: STATUS OF TECHNOLOGY AND ENVIRONMENTAL IMPACT

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16. ABSTRACT The report gives results of a literature review and personal contacts to ascertain what is being done in in-situ coal gasification and to collect existing environmental data. Study results indicate significant current interest and activity in the development of in-situ coal gasification. The report presents a general description of the chemistry, technology, and technological problems, along with detailed descriptions of the technical objectives, approaches, and results of ongoing projects. This presentation is used as a basis for summarizing the current state of knowledge regarding environmental issues. Although some information exists in the areas of water quality effects, air emissions, and ground subsidence, extensive additional work is needed during the technology development in order to eliminate non-problems and quantify real problems so that environmental control technology will be available when needed.

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ABSTRACT

A brief overview of the current status of U.S. and foreign in-situ coal gasification technology is presented in this report. In addition to summaries of specific U.S. in-situ projects, general discussions of the chemistry, technical problems and environmental considerations associated with in-situ technology are given.

In-situ gasification is being applied on a commercial scale today only in the U.S.S.R.; however, there are several other foreign countries, e.g., Great Britain, in which pilot-scale projects are underway. Field experiments are also being conducted in the United States. One such upcoming test, Hanna V, is designed to produce up to 90 MM scfd of low-Btu gas.

There are numerous unresolved technical problems associated with underground coal gasification (UCG). The primary problem in the pregasification phase has been achievement of a continuous linkage between injection and production wells. In the gasification phase the major problems have been associated with maintaining control over the process and producing a product gas of uniform quality. Some recent progress has been reported in these areas, however.

Associated with these technical problems are the potential environmental impacts of in-situ gasification which include groundwater contamination and air emissions from ground leaks. Environmental impacts from UCG gas purification and pollution control operations will be similar to the impacts associated with those operations in above-ground gasification facilities.

CONTENTS

		Page
Abstract		iii
Figures		viii
Tables		x
1.0	INTRODUCTION	1
2.0	OVERVIEW OF IN-SITU COAL GASIFICATION TECHNOLOGY	4
	2.1 General Description of UCG Technology	4
	2.1.1 Chemistry of In-Situ Coal Gasification	4
	2.1.2 Fundamental UCG Operations	5
	2.1.3 Unresolved Technical Problems	10
	2.2 Current UCG Projects	12
3.0	SUMMARY OF ENVIRONMENTAL IMPACTS OF UCG	22
	3.1 Water Quality	22
	3.2 Air Quality	27
	3.3 Subsidence	28
	3.4 Effects of Hazardous By-products or Wastes	29
4.0	COMPARISON OF IN-SITU GASIFICATION WITH ABOVE-GROUND MINING AND GASIFICATION	30
	4.1 Resource Recovery Efficiency	30
	4.2 Energy and Water Usage	31
	4.3 Technological Development Status	35
	4.4 Economics	37

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CONTENTS (Continued)

4.5 Land Usage and Impact 38

4.6 Water Pollution Potential 41

4.7 Air Pollution Potential 41

4.8 Health and Safety Aspects 42

Appendix

A ERDA'S LINKED VERTICAL WELL PROCESS AT HANNA, WYOMING 44

LVW Process Description 44

Hanna Test Site 45

Test Program - Status and Results 50

Water Quality Studies 65

Air Quality Studies at Hanna 72

B ERDA/LLL IN-SITU COAL GASIFICATION PROGRAM 81

LLL Process Description 81

Scope of Work and Project Status 89

C MORGANTOWN ENERGY RESEARCH CENTER 112

Scope of Work and Status 113

D TUSI IN-SITU LIGNITE GASIFICATION PROJECT 118

Process Description 120

Project Status and Scope 122

E UNIVERSITY OF ALABAMA - FEASIBILITY STUDY OF IN-SITU COAL GASIFICATION IN THE WARRIOR COAL FIELD 134

Process Features 136

Project Status and Results 136

CONTENTS (Continued)

F RANN DIVISION (NATIONAL SCIENCE FOUNDATION)/ UNIVERSITY OF TEXAS - IN-SITU CONVERSION OF TEXAS LIGNITE TO SYNTHETIC GAS 156

Scope of Work 158

Experimental Configuration 158

Project Status and Results 159

G OTHER U.S. IN-SITU GASIFICATION PROJECTS 160

Los Alamos Scientific Laboratory 161

Texas A & M University 161

Sandia Laboratories 162

Argonne National Laboratory 162

West Virginia University 162

Project Thunderbird 162

A. D. Little Study 162

H UCG PROJECTS OUTSIDE THE U.S. 163

BIBLIOGRAPHY 166

FIGURES

Number		Page
2-1	U.S. Patent on In-Situ Gasification of Coal Utilizing Non-Hypersensitive Explosives	9
4-1	Energy Return Ratio from Underground Coal Gasification Experiment, Hanna I	35
4-2	Energy Recovery Efficiency from Underground Coal Gasification Experiment, Hanna I	37
A-1	Diagram of Linked Vertical Well Concept of UCG	46
A-2	Location Map of LERC Underground Coal Gasification Experiment Site	47
A-3	Sequence of Linkage in the Hanna #1 Experiment	51
A-4	Well Pattern, Phase I of the Hanna II Experiment	55
A-5	Well Pattern for Hanna II, Phases II and III	58
A-6	Hanna III Well Pattern	63
B-1	LLL In-Situ Coal Gasification Concept	84
B-2	Block Diagram of LLL In-Situ Coal Gasification Process	85
B-3	Sorption Isotherm for Soluble Organic Components from Coal Tar on Subbituminous Coal	94
B-4	Sorption Isotherm for Ca^{+2} Ions on Subbituminous Coal	96
B-5	Location of Hoe Creek Test Site	103
B-6	Stratigraphic View of Hoe Creek Site	104
B-7	Schematic Diagram of Hoe Creek Experiment No. 1	109
B-8	Hoe Creek No. 2 Experiment - Five Spot Test	110

FIGURES (Continued)

C-1	A Longwall Generator Development Scheme	116
C-2	Longwall Generator Concept (Application to Power Generation Facility)	117
D-1	Process Flow Diagram for In-Situ Gasification Technological Test Site	121
D-2	TUSI In-Situ Lignite Gasification Project - Stratigraphic Cross Section of Test Area	124
D-3	Monitor Well Locations at Technological Test Drilling Site	125
E-1	Location of the Experimental In-Situ Gasification Study Area with Respect to the Warrior Coal Field in Alabama	137
E-2	Lithology Present in In-Situ Gasification Core Hole 1-A at Experimental Gasification Site	139
E-3	Gas Flow System for Laboratory Combustor (University of Alabama)	141
E-4	Leaching Apparatus	146
E-5	BOD Concentration Change with Time in the Contacting Experiments	150
E-6	COD Concentration Change with Time in the Contacting Runs	151
E-7	Organic Acids Concentration Change with Time in the Contacting Runs	152
E-8	Phenols Concentration Change with Time in the Contacting Runs	153
E-9	Chromium Concentration Change with Time in the Contacting Runs	154

TABLES

Number		Page
2-1	Summary of Ongoing UCG Research Projects	14
4-1	Comparison of UCG with Conventional Mining Plus Surface Gasification	42
4-2	Effects of Underground Coal Gasification Compared with Strip Mining Plus Surface Gasification	39
A-1	Chemical Composition of Subbituminous "A" Coal Core Samples from Sites 1 and 2 of the Hanna Coal Field, Hanna, Wyoming	49
A-2	Typical Composition of Dry Gas Produced in Underground Coal Gasification Experiment, Hanna I	51
A-3	Overall Average Composition of Product Gas from Hanna II, Phase I	56
A-4	Summary of Hanna II Results	57
A-5	Summary of Instrumentation Fielded for Phases II and III of the Hanna II Underground Coal Gasification Experiment	59
A-6	Typical Elemental Analysis of Coal Tar	67
A-7	Total Nitrogen, Total Sulfur and Titratable Nitrogen for Acid, Base and Neutral Fractions of UCG Coal Tar	68
A-8	Compositional Ranges of UCG Coal Tars	69
A-9	Composition of Aliphatics Fraction of Hanna I Coal Tar Sample	70
A-10	Tabulated Spectra on Separated Components from Tar Base Fraction of Hanna Carbonization Sample	71
A-11	Concentrations of Major Components in Wellhead Particulates	74
A-12	Composition of Wellhead Particulates	76

TABLES (Continued)

A-13 Ammonia, Hydrogen Cyanide, Carbonyl Sulfide and Carbon Disulfide Concentrations in the Production Gas

A-14 Vapor Phase Elemental Concentrations in UCG Production Gas

A-15 Particulate Concentration and Distribution in Flare Discharge Gas

A-16 Composition of Flare Discharge Gas

B-1 Gas Compositions Expected from Hoe Creek Experiments Nos. 1 (Air-Blown) and 2 (Oxygen-Blown)

B-2 Analysis of Ash (As Constituent Oxide) from Coal Typical of Hoe Creek Test Site

B-3 Results of Laboratory Inorganic Leaching Studies

B-4 Summary of Input Parameters for Water Quality Model Calculations

B-5 Summary of Input Data Used for Air Quality Calculations

B-6 Source Strengths for Various Effluent Gases

B-7 Summary of Hydraulic Characteristics of #2 Coal and Associated Strata - Hoe Creek Site

B-8 Chemical Quality of Groundwater from Various Strata - Hoe Creek Site 1

D-1 Baseline Water Quality Standards for Texas Lignite Gasification Project

D-2 Additional Baseline Quality Parameters of Water in Geologic Units

D-3 Sampling Frequency for Gasification Period

TABLES (Continued)

E-1 Properties of Coal Used.....

E-2 Experimental Parameters in Laboratory Leaching Studies.....

E-3 Water Effluent Analysis Exponential Decay Constants.....

SECTION 1.0
INTRODUCTION

The feasibility of in-situ gasification as an alternate coal conversion route is currently being assessed. This research effort is being carried out by federal and private organizations interested in determining its commercialization potential. The process consists of several distinct stages:

- Drilling conventional wells to the coal seam
- Ignition and linkage between wells
- Injection of air or oxygen and in some cases steam to induce the gasification reactions

A gas of either low or intermediate heating value is produced which, after cleanup, can potentially be utilized for electric power generation, upgraded to pipeline-quality gas or used for in-plant process requirements. The commercial feasibility of in-situ coal gasification will ultimately depend on the recovery efficiencies achievable and the economics. At this time these efficiencies are not well defined, although encouraging indicators are seen.

The concept of underground coal gasification (UCG) was first suggested in 1868 by William Siemens. Other early research was carried out by the Russian chemist, Mendeleev. In 1909 an American, Anson Betts, received the first patent on this type of process. Although small-scale experiments were conducted in England prior to World War I, the highest levels of activity on a large scale occurred in Russia beginning in 1931. After World War II interest was revived in several European Countries including England, France (Morocco), Belgium, Italy, Poland, and

Czechoslovakia, and in Japan, Canada and the United States as well. While the U.S.'s activities in this area died out primarily because of an unfavorable economic outlook, research was again initiated in the early 1970's under sponsorship by the Bureau of Mines, ERDA, private industry and other research institutions (L-871, L-748).

At the present time UCG is in full-scale operation in Russia and in pilot-scale stage in several other foreign countries such as Great Britain. Field experimentation at a less advanced level is in progress within the U.S., with one plan calling for possible production rates up to 90 MM scfd (Hanna V). The major test sites within the U.S. are:

- Hanna, WY (LERC)
- Gillette, WY (ERDA, Lawrence Livermore Lab.)
- Fairfield, TX (Texas Utilities Services, Inc.)
- Pricetown, WV (MERC)
- Adger, AL (University of Alabama)

Several other in-situ projects are also underway, although no field work has been done so far. These studies are being conducted by the University of Texas, Los Alamos Scientific Laboratory, Texas A&M University and Argonne National Laboratory. In addition, instrumentation development and testing is being carried out by Sandia Laboratories under ERDA sponsorship.

Underground coal gasification is considered a viable approach to the production of low-Btu gas. As such, it falls within the overall scope of the Environmental Assessment of Low-Btu Gasification and its Utilization (EPA Contract No. 68-02-2147, Exhibit A).

This document presents an overview of in-situ coal gasification technology and its potential environmental impacts. A general description of the chemistry, technology and technological problems involved is contained in Section 2.1, while the remainder of Section 2 briefly summarizes ongoing UCG projects. Detailed descriptions of the technical objectives, approaches and results of each are included in the Appendix. Section 3 summarizes the current state of knowledge regarding environmental issues. A comparative discussion of the technological and environmental aspects of UCG and conventional mining plus surface gasification is the concluding chapter of this report.

SECTION 2.0
OVERVIEW OF IN-SITU COAL GASIFICATION TECHNOLOGY

In this section a general discussion of UCG technology and descriptions of ongoing research projects are presented.

2.1 GENERAL DESCRIPTION OF UCG TECHNOLOGY

Many facets of in-situ gasification are generally applicable to all process variations. In this section the chemistry and basic mechanisms of coal gasification, basic process operational methods and unresolved technical problems are summarized. Much of the material presented here is based on project summary reports and other previously published literature (L-683, L-871, L-1216, L-5480, L-2643). These documents should be consulted for further details.

2.1.1 Chemistry of In-Situ Coal Gasification

In most in-situ processes two distinct phases are usually involved: carbonization and gasification. In addition, combustion supplies the heat required for both the carbonization and gasification reactions. Air reacts exothermically with coal and/or char producing CO_2 and H_2O as combustion products. These hot gases react with char to form product gas consisting mainly of CO, H_2, and CH_4. The combustion heat also promotes carbonization (or devolatilization) of coal resulting in methane, char, H_2O and coal tar. The tars are subject to fractionation according to the boiling points of the constituents as they move with the product gas away from the reaction zone. Heavier components condense in the coal seam while the lighter components remain with the product gas (L-683, L-8580).

Extensive laboratory-scale investigations of mechanisms, reaction products and kinetics of individual reactions and coal chemistry in general have been reported in the literature. The following reactions summarize some of the important steps involved in underground coal gasification (L-683):

Combustion	Coal + O_2 + H_2O + CO_2
Hydrolysis	Coal + H_2O + CH_4 + CO + higher hydrocarbons
Carbonization	Coal + C + CH_4 + H_2O
Bouduard (undesirable side reaction)	2CO + C + CO_2
Water gas reaction (gasification)	C + H_2O + H_2 + CO
Shift reaction	CO + H_2O + H_2 + CO_2
Methanation	$3H_2$ + CO + CH_4 + H_2O

The extent to which each of these reactions predominates and/or can be controlled under in-situ conditions is one of the principal subjects of current technical investigations.

2.1.2 Fundamental UCG Operations

Pregasification -

In-situ processing steps consist of pregasification followed by gasification and production. The main feature of pregasification is preparation of the bed by linking definable points in the coal seam such as the inlet and outlet boreholes or shafts. These linking processes generally increase the permeability of the coal bed and promote a smoother and faster gasification process. Some coal seams are naturally quite permeable and do not require "pregasification." The majority of coal seams, however, do require some pretreatment. Methods of

linking the desired points in the bed include electrolinking; pneumatic linking; fracturing by hydraulic pressure, explosives, or possibly nuclear reaction; deviated drilling and reverse combustion. This last method has been successfully used during the Hanna experiments (L-727, L-8730, L-5480).

Electrolinking is performed by passing a current through the coal seam carbonizing the coal. The rearrangement within the coal structure which occurs with this technique increases its permeability. Pneumatic linking involves pretreating the coal seam by passing high-pressure air through it before the gasification step. Fracturing the seam will obviously increase its permeability. The process of hydraulic linking involves injecting fluids under high pressure into the coal seam, thereby causing fracturing and hence increased permeability. Sand or some other inert agent is often subsequently injected into the fracture to prop it open after release of the pressure. Studies are also being conducted with liquid explosives. Another possible linking method is drilling horizontal or deviated holes through the coal seam from the inlet air shaft to the exiting gas shaft (L-871, L-683, L-2116, L-5480).

During the linkage phase of the vertical linked well technique practiced at Hanna, a path of increased permeability between the two wells is created by reverse combustion (combustion front propagation countercurrent to injected air movement). Combustion is initiated at the bottom of the production well with an electric heater and moves toward the injection well during a period of low-flow (~50 scfm), high-pressure (~250 psig) air injection. An increase in permeability occurs as the combustion zone nears the injection well allowing injection of larger quantities of air (~2000 scfm) at low pressure (~30-50 psig).

Gasification -

The gasification of the coal seam involves introducing the gasifying agents, contacting these agents with the coal, and recovering the reaction products. The methods of gasification can be classified as shaft type, shaftless type, or a combination of both. Shaft-type gasification requires the drilling of underground channels or passageways. Shaftless gasification requires only surface drilling operations. Current research is almost entirely devoted to the development of shaftless technology including: 1) the blind borehole method which employs a single hole with concentric pipes and 2) the percolation or filtration technique in which multiple boreholes are used. With this second approach, the coal seam is penetrated by boreholes at specified distances and gasification takes place between pairs of holes. This vertical linked well concept utilizes the natural permeability of the coal bed, often in conjunction with overt linking methods.

The gasifying agents used are oxygen, steam and carbon dioxide. These gases are introduced in varying proportions and contacted with the pretreated coal seam. During combustion oxygen reacts with the carbon in the coal to form carbon monoxide and dioxide. Water vapor reacts with the coal to produce carbon monoxide and hydrogen. Other reactions in the process (as listed in Section 2.1.1) produce additional carbon monoxide, carbon dioxide, and hydrogen. The exit gas from a UCG process consists of carbon monoxide, carbon dioxide, hydrogen, water vapor, nitrogen, methane, and various other volatile organics from the coal seam (L-8730). The product gas stream also contains heavier entrained hydrocarbons and hydrogen sulfide. The heavy hydrocarbons can be removed in a mechanical separator while the hydrogen sulfide must be removed by a chemical treatment method such

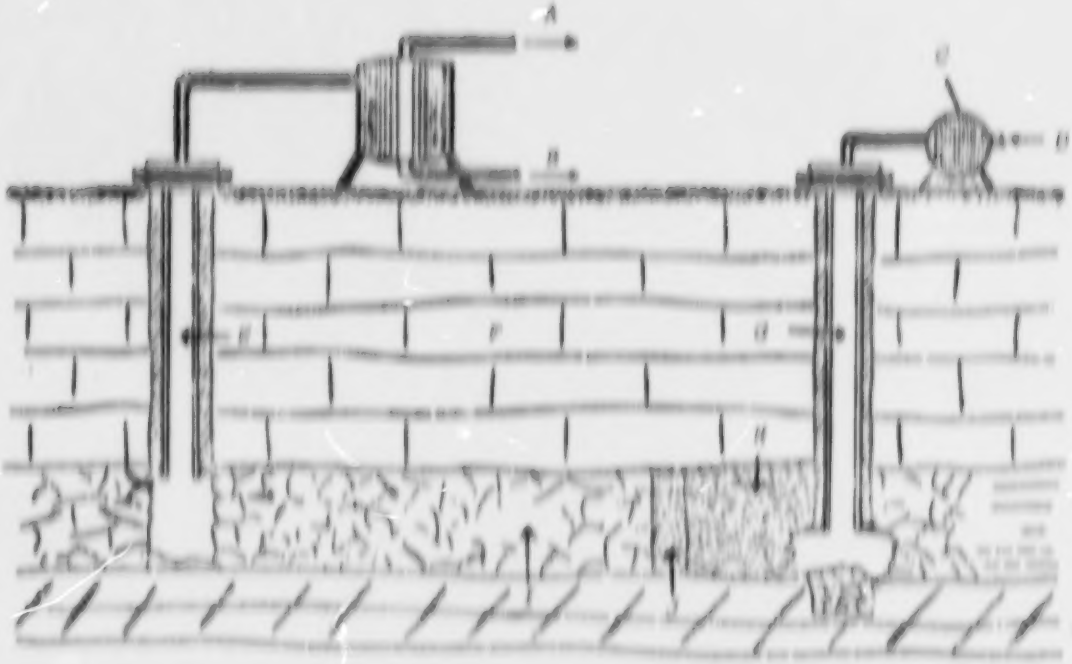
as amine absorption. A typical in-situ gasification process is diagrammed in Figure 2-1 (L-727).

Utilization -

Possible utilization schemes for the gas produced from in-situ processes include (L-1216, L-2645):

- Combustion in boilers to produce electricity
- Use in turbine or combined-cycle power generating systems
- Conversion to high-Btu gas for transport to consuming centers
- Conversion to liquid fuels via Fischer-Tropsch synthesis
- Utilization as a hydrogen source for ammonia or methanol synthesis
- Utilization as a reductant gas
- Utilization as a chemical feedstock

Since long-distance transport of low-Btu gas is generally regarded as economically unattractive, the product gas must either be utilized at the production site or converted to a pipeline-quality gas or liquid fuel.



KEY

A = Fuel Gas Product
B = Coal Tar Products
C = Compressor
D = Fuel Gas and/or Oxidizer
E = Production Well
F = Overburden
G = Injection Well
H = Charred Residual
I = Crumbled Coal
J = Combustion Front

ABSTRACT

Two or more wells are drilled into a coal seam. The wells are completed so as to isolate all other strata from the coal seam and a radially extended horizontal fracture is directed by introduction of a non-hypersensitive explosive under hydraulic fracturing conditions so as to connect the wells communicably. The explosive is ignited so that a horizontally and vertically directed fracture network is formed within the coal system. A combustion front is ignited and propagated through the fractured network to produce combustible gases and coal tar liquids.

Figure 2-1. U.S. PATENT ON IN-SITU GASIFICATION OF COAL UTILIZING NON-HYPERSENSITIVE EXPLOSIVES

(Source: No. 3,734,180 (May 22, 1973) V. W. Rhoades, Cities Service Oil Company)

2.1.3 Unresolved Technical Problems

Experience with in-situ gasification has revealed the existence of several potential technical difficulties. Numerous studies are underway to resolve or further define the causes of some of these problems.

Achieving positive connection between the inlet and outlet wells during the pregasification phase has been accomplished by two methods. Directionally drilled boreholes is the first method and has been proven to be effective for various types of coal. The second technique is linkage by reverse combustion. This method was successfully demonstrated during the Hanna II tests using a subbituminous coal seam. The effectiveness of reverse combustion still needs to be demonstrated on other coal types.

Numerous problems during the gasification phase have been pointed out. The majority deal with the question of maintaining good control over the process.

The major objectives of any UCG control strategy are to achieve a uniform gas quality and production rate. Contact between the coal and reactant gases should be controlled so as to minimize production of CO_2 and H_2O, and to maximize oxygen consumption and efficiency of coal usage. These objectives are relatively easy to meet during the intial period of any test but become more difficult to ahcieve as the void space increases causing poor gas-coal contact.

An associated problem is the development of accurate process monitoring techniques to follow the gasification or linkage process from the surface and to provide data for process control. Specific problems include (L-5480, L-871, L-683, L-1126, L-2645, L-847):

- Establishment and maintenance of ignition
- Directional control of the flame front
- Uneven burning due to nonuniformity in coal bed
- Control of temperature in the reaction zone
- Plugging and reduced permeability due to deposition of tars and slags
- Gas leakage from the gasification area (safety and environmental as well as efficiency loss aspects)
- Penetration of groundwater into the reaction zone resulting in oxygen loss, temperature fluctuation, possible extinguishing of combustion process, and later groundwater contamination
- Control of roof collapse which can cause decreased permeability and increased oxygen bypass as well as create subsidence problems in some situations
- A decrease in the product gas heating value as gasification proceeds due to the poor gas-coal contact that results as the void fraction of the coal bed increases and/or as water enters the gasification zone
- Control of shut-down

Some problems are also foreseen in the utilization of the product gas. These problems are primarily due to fluctuations in gas production rate flow and quality. Solutions to these problems are being sought. No major technical problems are envisioned in this area; however, upgrading the product gas to a pipeline-quality fuel or gas has not yet been demonstrated to be practicable.

Several general disadvantages associated with in-situ gasification have also been noted (L-9480, L-1326, L-681, L-727, L-8730). Coal energy recovery at this time remains low or ill-defined. The underground process itself is not completely understood; therefore, extrapolation from small field tests to the commercial scale is not yet feasible. Site-related variations pose more difficult problems than other mineral extraction processes because thermal and chemical as well as mechanical aspects are involved.

Intimately tied up with these technological problems are associated potential environmental impacts such as groundwater contamination, air quality degradation and subsidence. These problems are specifically addressed in Section 3.0 of this report. Specific approaches to defining these problems which are currently under investigation are discussed in Section 2.2.

2.2 CURRENT UCG PROJECTS

In this section summaries of ongoing studies related to in-situ coal gasification are presented. The major efforts in the U.S. include the ERDA-funded projects at Hanna (LERC) and Gillette (LLL), Wyoming, and Pricetown, West Virginia (MERC); Texas Utilities' lignite gasification test; and the University of Alabama's in-situ project. These and some additional smaller

scale investigations are summarized in Table 2-1. Foreign projects are also briefly covered. More detailed descriptions of the objectives, scopes and available results to date are presented in the Appendix.

Table I-1. SUMMARY OF ONGOING UCG RESEARCH PROJECTS

Objectives	Current status	Results: Technological	Results: Environmental
Hanna I - Hanna - Lindahl Vertical Well Process **LOCATION:** Hanna, Wyoming **OWNERSHIP:** Laramie Energy Research Center (LERC)			
Overall objective: Evaluate the technical, environmental and economic feasibility of UCG in a thick, moderate subbituminous coal seam.	The first element of the U.S. program. The field test programs have been successfully completed and data are released.		
Hanna I - March 1973 - March 1974. Investigate forward and reverse reactivation on linkage breakthrough and forward gasification in a 7-well pattern using air as the oxygen source.	Completed	Forward reactivation linkage unsuccessful. Reverse reactivation linkage was successful at high pressure, low-volume injection conditions. During gasification tests, production rate averaged 1.5 million scf/day with average product gas heating value of 126 Btu/scf. It was demonstrated that groundwater influx and gas leakage can be controlled by air injection pressure. Directional control of reactivation front was achieved.	No measurable gas leakage from reactive zone has occurred to date. Similarly, no measurable surface subsidence has occurred. Condensate from the product gas stream collected during Hanna I and II have been separated into organic (coal tar) and aqueous fractions. The water fraction along with some additional water samples from downhole sampling are presently being characterized by GC-MS to identify organic components which might potentially enter groundwater systems.
Hanna II, Phase I - April - Aug. 1977. Evaluate coal seam permeability, linkage site geometry, fracturing and reverse reactivation, establish gas-flow relations for linked vertical wells in a 7-well pattern. Hanna II, Phase II - Nov 1 - 31, 1978. Gasification period. Investigate process control capabilities during the linkages and the gasification tests in a reverse 7-well pattern. Injection rate was varied during gasification. Extensive monitoring instrumentation utilized (Tandem Lab.).	Completed Completed	Control of reverse reactivation linkage was demonstrated. Air injection rate could be reduced by a factor of 20 with only a 50% decrease in gas heating value (avg. 152 Btu/scf). Gas production totalled 182.1 million scf. Narrow linkage path can be placed at depth of seam. Gasification front could have been as wide as 80 feet. No dramatic effect of varying injection rate during gasification. Overall improved gas quality (232 Btu/scf) and resource utilization attributed to high injection rates and use of back-pressure to control inflow of groundwater.	The organic fraction has received considerable attention. After separation into tar acids, bases, neutral aliphatics, and neutral aromatics, each fraction is being analyzed. The tar acids are almost exclusively phenolic in nature, while the tar base fraction consists pyridines, anilines and quinolines with some substituted pyridines also present. Preliminary results indicate that the aliphatic neutrals apparently contain a normal saturate series ranging from C_{10} to C_{22} with some branched saturates and a particularly heavy level of C_{20} branched chains. Some low concentrations of unsaturated or cyclic compounds were detected. Results of product gas monitoring during Phase II, Phase III, indicated that no enforcement problems should be encountered in the area of air quality monitoring. Particulate loading ranged from 0.0025-0.3 lb/mcf, with the majority being 1b. Hg, Pb, Cd, Cr_2 and trace elements were also determined. Hg levels were lower than expected, and CHC and Cr_2 varied with time, with CHC decreasing and Cr_2 increasing over the monitoring period. The only trace elements of those monitored to exceed 1 ppm were Ba and Cu.
Hanna II, Phase III - June 24-July 31, 1979. Gasification period. A time-delay reverse reactivation between two linkage pathways established in Phase II was planned, to be followed by gasification of the zone not exposed by the 4 wells.	Completed	Attempt to reverse broad linkage path was not successful. Three therefore modified to another two-well here. Excess water greatly lowered heating value of gas (117.8 Btu/scf) and thermal efficiency of the process.	

Continued

Table 2-1. Continued

Objectives	Current status	Results: Technological	Results: Environmental
Rosa III – Third Quarter 1977 [illegible]	Planned		
Rosa IV – [illegible]	Planned		
Rosa V – [illegible]	Planned		
	PROJECT: [illegible]		
	LOCATION: [illegible]		
	PARTICIPANTS: – [illegible]		
Overall objective – [illegible]			
Fundamental Laboratory Studies – [illegible]	Ongoing	[illegible]	[illegible]

Continued

Table [illegible] Continued

Objectives	Current Status	Results: Technological	Results: Environmental
			be released as a slug. Sorption isotherms and distribution coefficients (K_d) were then determined. Goal was an infinite sorbent for SO_2 K_d for organics dependent on the initial concentrations and ranged from 2.0 to 50.0 as concentration decreased from 2000 ppm. Co was evident by coal to a much less extent than the organics.
Water Quality Dispersion Model – Describe groundwater plume movement based on laboratory-defined pollutant leachability and sorption data as well as hydrogeological site description.	Preliminary results are available	The model has been developed and many input parameters have been defined.	The organic plume is predicted to move only [illegible] m in 1000 years and its concentration will be reduced from 2000 to 200 mg/l. The Co^{2+} plume will move [illegible] m downstream in 700 years and its concentration will be [illegible] of the original "input" concentration.
Air Quality Modeling – Model air pollution plume expected to result from the Creek gasification test.	Preliminary conclusions are reported		General conclusion reached is that the Bee Creek site should not produce adverse air quality conditions even under worst operating conditions.
Pressure Field Test – Conduct small-scale high-explosive fracturing test.	Completed	Measured permeability and fracturing were in good agreement with predictions for the one- and two-dimensional stress-strain codes.	
Bee Creek Experiment No. 1 – This preliminary test was a simple two-spot fracturing test to improve the permeability at the area. Original plans called for air gasification to follow (see Phase II below).	Completed (December 1, 1975)	Preliminary explosive fracturing resulted in lower than expected permeability increases. Therefore, a second phase was planned before gasification (see Phase II below).	
Bee Creek Experiment No. 1, Phase II – This revised plan was calls for drilling new production well closer to the injection well. Following dewatering, gasification via a forward burn is planned. If plugging occurs, reverse combustion may be called for prior to gasification.	Drilling in progress		
Bee Creek Experiment No. 2 (Five-Spot Test) – The objective of this test is to explosively fracture and dewater a suitable tree, then over a 7-month period gasify [illegible] tons of coal in a 2-foot thick block. Gaseous and liquid effluents will be monitored.	Drilling operations were halted December 1975. The future status of this experiment will depend on the outcome of Bee Creek 1, Phase II.		

Continued

Table 2-1. Continued

Objectives	Current status	Results: Technological	Results: Environmental
	PROJECT: [illegible] Lignite Gasification Project LOCATION: [illegible] PARTICIPANTS: [illegible]		
The overall objective is to determine the applicability of Benzine technology to deep East Texas lignite deposits for electric power generation. In the first test, the heating value and quantity of gas produced, process economics, and environmental impacts will be investigated.	Drilling and other site preparation work was initiated in March 1975. The first burn took place in August and September 1976. Groundwater monitoring is continuing. [illegible] analyses of results are encouraging a pilot-scale operation may be considered.	The operation was shut down after 20 days when the gas quality became too inferior to continue. Operation under much reduced pressure was necessary to control in-situ water quality. No data was available regarding gas quality.	Results of groundwater monitoring showed decreased pH and increased conductivity levels in 4 wells (3 in the lignite room and one in the overlying aquifer). The pH drops were noted as soon as 1 day after air injection was initiated, with the conductivity changes occurring a few days later. After 5-10 days the pH levels appeared to live out but at below-normal levels. Other analyses were either inconclusive or not yet available.
	PROJECT: [illegible] Compact Generator Concept LOCATION: [illegible], Wetzel County, West Virginia PARTICIPANTS: - Morgantown Energy Research Center (MERC) - Consolidation Coal Co. - Continental Oil Co.		
Overall Objective - Identify controlling mechanisms in UCC using developed drilling technology. Specific objectives include improvement of resource utilization, optimization of product gas heating value and composition, and minimization of environmental degradation and cost.			
Theoretical studies - Conduct process simulation of coal test, exploring internal effects such as shrink-swell behavior, phase changes, etc.	In progress		
Laboratory Studies - Investigate actual physics of UCC, quantification of mechanical and thermal effects and physical properties, and supply data for process simulation studies.	In progress		
Field Project - Demonstrate feasibility of new directional drilling technology.	Drilling of new directional hole in Hanford Bed Tidbury with the vertical hole has not yet been achieved.		

Continued

Table 2-1. Continued

Objectives	Current Status	Results: Technological	Results: Environmental
	[illegible]: Supervising of Alabama [illegible]: Barrier Coal Field near Adger, Alabama [illegible]: – University of Alabama – Alabama Power Co. (in-sequence) – Mineral Resources of Alabama (in-sequence) – [illegible] (in-sequence)		
Overall objective – See that study of the technical feasibility or [illegible] of this [illegible] of [illegible] coal.	One year into project		
Site Selection – Requirements include [illegible] less than 1 meter thick.	Completed		
Characterization of Site – Characterize coal, geology and [illegible] in vicinity of proposed test site.	Significant progress has been made.	Properties of coals in Barrier Field have been compiled. Most are ranked as high or medium bituminous coals.	
Air Acceptance Tests – Measure rate at which air or [illegible] gas can be forced into a coal seam through a drilled and cased borehole at a specified pressure.	In progress – two test holes have been drilled and more are planned.	No result is reported yet.	
Laboratory Combustor Studies – Provide data for correlation between product gas quality and input variables.	Four meaningful results have been obtained. This part of the program is continuing.	Results are summarized in the Appendix.	
Investigation of Linking Techniques – Evaluate [illegible] fracturing for initial permeability development and possibly reverse combustion to complete the linkage. [illegible]'s deviated drilling technology is also being considered.	In progress	No results reported yet.	
Develop Numerical Analysis Methods – This is a support task involving an analysis of results from other tasks to supplement laboratory and field studies. Topics under study include [illegible] and lateral extent of combustion front during reverse burn and associated heat transfer and fluid flow considerations.	In progress	No results reported yet.	

Continued

Table 3-1. Continued

Objectives	Current status	Results: Technological	Results: Environmental
Groundwater Contamination Studies - Define potential long-term contamination of groundwater, considering both organic and inorganic species. This task involves laboratory leaching, modeling, studies and baseline groundwater monitoring activities.	In progress		Results of leaching studies on laboratory-derived gasification residues were reported in terms of decay coefficients and initial release concentrations. Leaching curves were fitted by an exponential decay equation; phenols, however, did not fit this curve. The potential conclusion reached to date is that no long-term problems should result from IGC although initial releases of some components exceeded available water quality standards used in the study. Particle size was found to have a significant effect.
	PROJECT: University of Texas Support for Texas Lignite Gasification LOCATION: Site not yet selected. PARTICIPANTS: - University of Texas - [illegible] - Texas Utilities Services Co. - Continental Oil Co. - Mobile Oil Co. - State of Texas		
Determine geological, physical and chemical conditions conducive to IGC. Develop model for physical and chemical processes. Demonstrate IGC on a bench scale. Select site for field tests based on engineering and geological data.	The program has been underway for 7½ years. Significant work has been done to characterize potential water areas for a site has not been selected. A bench-scale reactor has been designed and constructed. A process simulation model has been developed and an economic model in existing completion.	Based on results to date, it has been concluded that IGC is technically feasible for application to deep basin Texas lignite. It appears that in-situ gasification will expand the extraction limits for coal by a factor of ten over strip mining.	
	PROJECT: Texas A & M Project LOCATION: Blue College Station, Texas PARTICIPANTS: Texas A & M University		
Evaluation of process-related ties linkage and subsequent forward gasification with air for in-situ gasification of Texas lignite.	Not getting underway.	No results reported yet.	

Continued

Table 2-1. (continued)

Objectives	Current status	Technological	Economical
	PROJECT: Los Alamos PARTICIPANTS: - Los Alamos Scientific Laboratory - [illegible] (to be proposed)		
Evaluation of process based on gasification by CO_2 and H_2, rather than steam and O_2 as are the applications in water-wall regions of the Gasifiers.	Initial conceptual assessment being carried out for Los Alamos. Plan to submit the proposed process to [illegible] Los Alamos Laboratory.		
	PROJECT: Combustion and Instrumentation development LOCATION: - Boston, Massachusetts - [illegible], Washington (Center) PARTICIPANTS: - Combustion Laboratories - [illegible] (sponsors)		
Development of instrumentation for monitoring MHD generators.	Instrumentation developed to date was carried during the Mono II tests. Plans also exist for probable applications and testing at the [illegible] site.		
	PROJECT: Argonne National Lab Project PARTICIPANTS: - Argonne National Laboratory - [illegible] (sponsors)		
Investigation of coal/slag/seeding conditions and product characteristics for the gasification of coal and char using steam and oxygen. Also, evaluation of using beneficiation where as where needed.			
	PROJECT: West Virginia MHD Electrode PARTICIPANTS: - West Virginia University - Service of Water		
Contact refractory studies on ceramic gasifications.			
	PROJECT: [illegible] Applications PARTICIPANTS: [illegible]		
Development of MHD on commercial scale.	There are currently four [illegible] commercial [illegible] of the electrical power utility industry presently [illegible] MHD in America.		The technological problems are considered [illegible] information.

(continued)

Table 2-1. Continued

Objectives	Current status	Results: Technological	Results: Environmental
	PROJECT: Belgium/West Germany Cooperative Study LOCATION: Specific text site not yet noted PARTICIPANTS: - Belgium - West Germany		
Develop in-situ technology for utilization in coal fields located in New Germany [illegible] through northern Belgium and the Netherlands. Possibly combined-cycle utilization will be tested. If successful results are achieved, substitution of hydrogen for air to obtain high-Btu gas may be attempted.	Test getting underway. Initial testing planned for early 1978.	No result is reported yet.	
	PROJECT: Canadian [illegible] Project PARTICIPANTS: Alberta and British Governments		
		A test [illegible] has been [illegible].	No results have been reported.
	PROJECT: Pilot-scale [illegible] Project LOCATION: [illegible] Station near Sheffield PARTICIPANTS: - National Coal Board - Central Electricity Generating Board		
In-situ gasification of a low-grade coal with high mineral content and subsequent utilization for electrical power generation is being tested in a 5-[illegible] unit.	Work has been underway since 1957.	Specific results not yet reported.	
	PROJECT: Czechoslovakian [illegible] Project LOCATION: Northern Bohemia PARTICIPANT: Czechoslovakia		
Development and application of lateral gas removal technology to gasification of brown coal in northern Bohemia. Industrial-scale project was planned involving 220-[illegible] power generating unit, tar and [illegible] removal units, and wastewater treatment.	Current status unknown.	Trial tests initiated in 19[illegible] were successful.	

SECTION 3.0
SUMMARY OF ENVIRONMENTAL IMPACTS OF UCG

The purpose of this section is to summarize real and potential environmental problems associated with in-situ coal gasification. Ongoing studies of air and water quality impacts were summarized in Section 2.2; details are available in the Appendix. Significant results forthcoming from those efforts will be summarized here.

The areas addressed in this section include:

- Water quality impacts
- Air quality impacts resulting from the production and utilization of product gas
- Subsidence
- Effects of hazardous by-products or wastes

3.1 WATER QUALITY

The potential for contamination of groundwater is considered by some to constitute the most serious environmental threat posed by underground coal gasification. While this aspect of UCG is still in the definitional stages, more work has been done in the water quality area than in any other area of potential environmental concern. Degradation of groundwater could result from any of the following three sources:

- Organic contaminants in the tars produced during carbonization or gasification

- Inorganic salt or trace element loading due to dissolution of ash

- Changes in flow patterns or rates resulting from subsidence or interconnection of aquifers by fracturing

In addition, disposal of water pumped from the coal seam during dewatering operations may constitute a surface water problem depending on the nature and level of contaminants found in the water.

Due to hydraulic gradients, migration of groundwater will occur through coal seams and burned-out areas which lie below the water table. This may cause soluble components in or sorbed on the ash or char to be leached out and transported away from the gasification site. An increase in dissolved organic material could result from partial dissolution of coal tars formed during gasification. As a general rule, the lighter, more soluble tar fractions will be swept to the surface with the product gas, while heavier, less soluble fractions tend to remain in the ground. Over a long period of time, however, slow dissolution of even these fairly insoluble components might occur.

Similarly, incorporation of inorganic salts and trace elements into the groundwater regime could occur via leaching of ash components. In order to develop a predictive capability for levels of contaminants in the groundwater exiting the burn area, characterization of gasification residues and their short- and long-term leaching behavior must be determined. Actual field data from samples of groundwater exposed to in-situ gasification materials can supply additional valuable insight to the problem.

Several types of studies have been performed or are in progress in order to characterise water that comes in contact with product gas (via gas leakage) or gasification residue. These investigations include bench-scale leaching of carbonization and gasification residues (LLL and University of Alabama), analysis of organic condensate from product gas (Hanna), characterization of water samples from burn areas (Hanna and fUSI), and groundwater monitoring at gasification test sites (Hanna, TUSI, and planned at LLL). Additional groundwater studies are planned for all these projects.

Results to date indicate that coal tar components include:

- phenols
- pyridines
- anilines
- quinolines
- aromatic hydrocarbons

Based on general solubility characteristics of these potential water pollutants, phenols pose the greatest threat, while pyridines and anilines are also regarded as soluble and therefore likely to be present in the water. Quinolines, which are somewhat less soluble, may be present at trace levels. Aromatic hydrocarbons are not expected to present a significant hazard to water quality.

The dispersion of soluble contaminants will be a function of groundwater flow and the sorptive properties of the materials through which the leachate passes. Laboratory studies are in progress at Lawrence Livermore and at the University of Alabama to determine the sorptive capacities of coals and chars. The results will be used in modeling studies designed to describe

groundwater plume behavior. Results to date indicate that coal appears to be a very sorptive material for both organic and inorganic species. In one study in which tap water was used as the leaching medium, trace metal levels in the effluent were lower than baseline levels; that is, the coal appeared to remove not only those trace metals leached from the gasification residue but also those present originally in the tap water. Concentrations of those species for which intial leach concentrations exceeded available water quality standards* (NH_3, COD, phenols) were lowered to undetectable or acceptable levels by passage through the coal.

Results to date from the LLL modeling study also indicate that coal is a very sorptive material for both organic species (individual components not measured) and inorganic ions. Based on this fact and the slow flow rate exhibited by groundwater, plume movement should have negligible short- and long-term effects upon most groundwater regimes. Some of the assumptions and experimental methods employed, however, may have optimistically biased these findings.

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* *Promulgated and recommended standards for comparison in the referenced study include:*

BOD, COD	*Effluent averages of samples; Tuscaloosa (Alabama) Wastewater Treatment Plant.*
BOD	*Effluent monthly average set by EPA as suitable for Tuscaloosa Wastewater Treatment Plant.*
NH_3 *Nitrite* *Sulfate* *Phenols*	*Recommended maximum level for public water supply (Water Quality Criteria 1972)*
TDS	*Desirable maximum level for public water supply; may be exceeded if concentration of other individual substances remains below recommended limits (Water Quality Criteria 1972).*
Nitrate	*Maximum level set by law for public water supply (Federal Register, December 24, 1975).*

All of the test sites planned or operating include instrumentation and/or sampling wells for monitoring groundwater quality. The only project for which data are presently available is the TUSI lignite gasification project in East Texas. These results are very preliminary, but noticeable increases in conductivity and decreases in pH were measured in some wells located in the coal seam and the immediately overlying aquifers. Limited data indicate the presence of phenols in the overlying aquifer as well. Temperature and NH_3 levels were not affected, while sulfate levels showed a decrease. Based on the data available, no long-range conclusions can be drawn at this time, but monitoring is continuing at the site.

Another potential water quality problem which has received limited attention is the disposal of water removed from the gasification zone during dewatering operations. Although no decisions can be made until the quality of this type of water has been more fully characterized, the following utilization/disposal options have been suggested.

- Pumping the water to nearby stock tanks for livestock use
- Using the water for dust suppression on roads
- Surface treatment for phenols and/or pyridine removal by some method such as activated carbon
- Reinjection into the reaction zone or deeper saline aquifers

3.2 AIR QUALITY

Only one investigation of the potential impact of UCG on air quality has been conducted to date. Product gas and flare discharge at the Hanna test site were monitored for particulate matter content and fourteen trace components. These included carbonyl sulfide (COS), carbon disulfide (CS_2), ammonia (NH_3), hydrogen cyanide (HCN), mercury (Hg), lead (Pb), cadmium (Cd), arsenic (As), selenium (Se), sodium (Na), potassium (K), lithium (Li), vanadium (V), and calcium (Ca). The primary concern with Na, Ca, V, Li and K is their corrosive effects should the product gas be utilized in gas turbines. The other five trace elements are of environmental concern.

The particulate loading in the product gas ranged from less than 0.0025 gr/scf to 0.36 gr/scf, with the majority of the particulate matter being <2μ in diameter. Only one out of six samples deviated significantly from this size distribution; in this one case greater than 85 percent of the particulate was <2μ. Since this occurred near the end of the monitoring period, it was surmised that the natural filtering capacity of the coal in the seam was diminishing as the test proceeded, allowing larger particles to be entrained with the product gas.

The results of the NH_3, HCN, COS, CS_2, and trace element measurements were also reported. The NH_3 emissions were relatively constant and lower than previous rules of thumb had predicted; i.e., that 80 percent of the fuel nitrogen is converted to NH_3. One explanation for the observed lower values is that some ammonia may have been scrubbed out by the condensables in the product gas. It is also possible that this general rule of thumb may be invalid for in-situ coal gasification.

Levels of HCN, COS and CS_2 were low, as expected. The latter two were observed to be time dependent, with COS trending downward and CS_2 upward. Analytical results for HCN were relatively uncertain. Of the trace elements monitored only Na and Ca exceeded the 1 ppm level.

The overall conclusion reached from this study was that no unforeseen problems should be encountered in the area of air quality monitoring. Development of a broad data base is needed, however, in order to verify this preliminary conclusion.

3.3 SUBSIDENCE

Instrumentation for monitoring subsidence effects has been installed at all operating test sites. To date, no detectable surface movements have been observed at Hanna. Information of this nature from the TUSI site has not been made available. No tests have yet taken place at the other project sites. Since any measured subsidence will be related to geologic conditions at the particular site and may not be generally applicable to other sites, it will be necessary to gather this type of data for a range of sites before any general conclusions as to the severity of the subsidence problem can be drawn.

Subsurface subsidence is generally most likely to occur as a result of roof collapse in the void area created as gasification proceeds. This could have three direct effects: the fallen material could decrease the permeability of the burn area, reduce the flow of oxygen and, in extreme cases, extinguish the burn. A second possible effect is the alteration of groundwater flow patterns. This could increase the potential for groundwater contamination or could alter the gasification process by reducing the burn temperature or even extinguishing the flame. There is also some indication that roof collapse results in a temporary

increase in atmospheric particulate emissions. Another possible effect of subsidence is increased potential for gas leakage, resulting in a drop in process efficiency and/or possible ground-water contamination by the escaping gases.

3.4 EFFECTS OF HAZARDOUS BY-PRODUCTS OR WASTES

Another related potential problem is spillage of coal tar liquids condensed from the gas product stream. In one minor incident reported, some of this liquid was spilled on the ground; the vegetation was killed but new growth was observed in most contaminated areas the following season. The herbicidal and other toxicological properties of the tar liquids require further investigation.

SECTION 4.0
COMPARISON OF IN-SITU GASIFICATION WITH ABOVE-GROUND MINING AND GASIFICATION

Commercialization of in-situ gasification will be in direct competition with conventional coal mining and above-ground gasification processes. This section briefly discusses technological and environmental aspects which should be considered in comparing these alternate coal conversion routes. Economic factors are not addressed in any depth in this discussion although they would obviously be included in any definitive comparison. Because UCG is in an early stage of development there are insufficient hard data regarding commercial-scale gasification facilities and environmental impacts; therefore, the following discussion is limited to general comparisons of these important issues:

- Resource recovery efficiency
- Energy and water usage
- Technological development status
- Economics
- Land usage and impacts
- Water pollution potential
- Air pollution potential
- Health and safety aspects

4.1 RESOURCE RECOVERY EFFICIENCY

The application of in-situ coal gasification is estimated to expand the extraction limits for coal by a factor of ten over strip mining (L-9168, L-9169). This is based on a comparison

of overburden to seam ratios which define the limits of economic attractivenuss. For in-situ this ratio is 150:1, while that associated with strip mining is 15:1. Of the total U.S. coal resources, only 12 percent is considered recoverable by present coal mining methods (L-4822). In-situ gasification could expand the base of recoverable coal to include deep, thick seams overlain by excessive overburden and steeply dipping seams presently not considered minable.

In conventional room-and-pillar mining, coal recovery is typically 60 percent because some coal must be left in place to provide support for the overburden (L-1216, L-871). Coal utilization efficiencies for in-situ processes are presently estimated to be of similar or greater magnitude. The coal utilization estimated for the Hanna I experiment, based on material balance calculations, was reported to be 63 percent (L-6631). This represents the percent of coal affected (i.e., either carbonized or completely gasified). Recovery efficiencies of latent energy in the coal are addressed in Section 4.2. Recovery calculations from a more recent test (Hanna II, Phase III) showed that the total utilization in the 4-well pattern was 6700 tons compared to 4600 tons within the 60- by 60-foot square, indicating a high overall areal sweep efficiency (L-9118).

Another aspect of resource utilization to be considered is that in-situ gasification might impact the extraction of other minerals (L-683). Decisions impacted by this factor must be made on a site-specific basis.

4.2 ENERGY AND WATER USAGE

The two resources considered here are water and energy. A comparative estimate of water usage for two base cases described in Table 4-2, underground coal gasification and strip

Table 4-1 COMPARISON OF UCG WITH CONVENTIONAL MINING PLUS SURFACE GASIFICATION

	Underground coal gasification	Conventional mining plus surface gasification
1. Resource recovery	Extraction limit (overburden: seam ratio) of 150:1. In-situ increases total recovery of present U.S. coal resources. Coal utilization for Hanna I was 63%, while apparently even greater for later Hanna tests.	Extraction limit of 15:1. Only 12% of U.S. coal resources recoverable by conventional coal mining. Resource recovery of 50% is typical of room-and-pillar mining.
2. Energy and water usage	The water requirements of a UCG process should be somewhat less than those of an equivalent strip mining-surface gasification operation.	Water usage rate for a given strip mining-gasification case is given in Table 4-2.
	Energy return ratio of approximately 4 and overall energy efficiency of ~50% calculated for Hanna I experiment.	Similar energy recovery efficiencies for in-situ and stirred-bed producer have been calculated. Energy input for conventional mining not included, however.
3. Technological development status	Most advanced U.S. project (Hanna) has been successfully operated at less than pilot level. Pilot-scale project to be operational in 1981 is planned. Outside U.S. UCG is commercialized.	Low-Btu gasification is commercialized, although in U.S. only small gasifiers are presently in operation. There are still unresolved problems with high-Btu gasification.
4. Economics	Equipment costs and UCG in general will probably be less. Transport of low-Btu gas from remote locations is economically unfeasible.	High coal transport costs between mine and gasification facility. Overall costs will probably be higher than for UCG.

Continued

Table 4-1. Continued

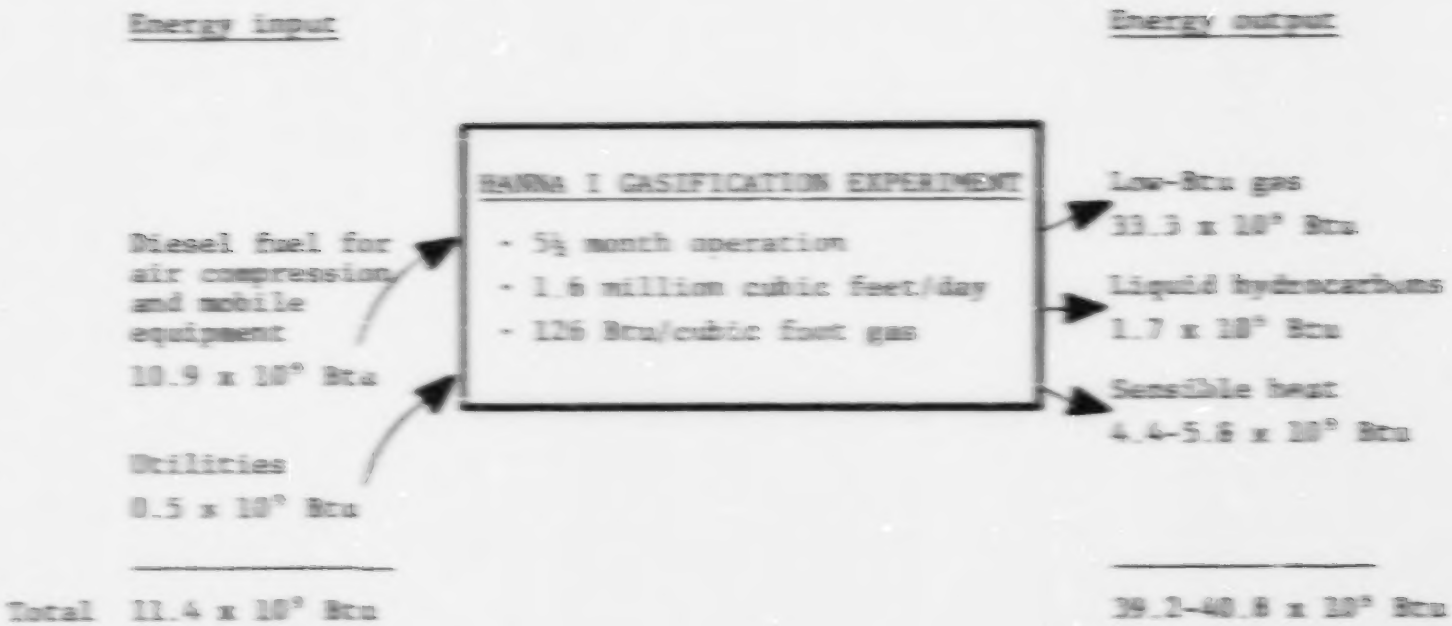
	Underground coal gasification	Conventional mining plus surface gasification
5. Land use and impacts (refer to Table 4-2)	Minimal land disturbance. Disposal requirements only for coal tar (if not marketable) and recovered sulfur. Future land use applications not yet determined.	Considerable land disturbance and massive reclamation requirements associated with strip mining. Additional solid waste disposal problems compared to UCG. Future land use typically restricted to recreational and agricultural purposes.
6. Water pollution potential	Still undefined at this time. Potential problems of unconfined groundwater contamination by inorganic components of ash, organics from coal tar, and gas leakage.	Both strip and deep mining methods have tremendous impact on water quality in the form of acid mine drainage. Pollution control methods are difficult to apply since source is uncontained. Major source of wastewater from above-ground gasification is ash quenching. Can be minimized by recycle and methods are available for treatment.
7. Air pollution potential	Potential gas leakage from outcrops and high-pressure equipment. Fugitive dust from vehicular traffic and site preparation. Process sources include gas purification units (similar to above-ground facilities).	Fugitive dust from mining activities, particularly strip mining, vehicular traffic and site preparation activities. Process emission sources include gas purification (similar to UCG) plus coal preparation and product up-grading units (high-Btu only).
8. Health safety aspects	Minimal.	High degree of occupational safety and health hazards associated with deep coal mining. Investigations in surface gasification facilities in preliminary stages.

mining plus surface gasification, yielded the same water requirements on a yearly basis, i.e., 11 million cubic meters per year. This comparison may or may not be meaningful, however, because of the various factors that influence water usage in the gasification processes. Stoichiometrically UCG and surface gasification have similar water requirements. However, for UCG, some of the water required is present in the coal seam. There will also be some difference in the quantities of process water the two gasification operations will require. The water quantity comparison specified above does not consider the differences in the quality of the water required by the processes.

Energy usages obtained from the in-situ Hanna I experiment and a stirred-bed producer were calculated and compared in one study reported in the literature (L-4822, L-8520, L-6921, L-6631). The results indicated that similar energy recovery efficiencies were achieved from both systems; however, energy used in coal extraction was not considered in the stirred-bed producer case.

The rate of energy return is defined as the ratio of total energy produced from a system to the total energy consumed in running the process. Energy available from the coal is not considered in this indicator, which must be greater than one in order for a process to be commercially feasible. The input and output parameters considered in calculating the energy return ratio for the Hanna I experiment are shown in Figure 4-1. This ratio was 3.5-3.6, but it was noted that the use of more efficient compressors and an improved flare system could increase this factor to 8.0-8.3 (L-4822, L-6631).

A second factor used to compare processes is the energy recovery efficiency. This is the ratio of energy produced



$$\frac{\text{Energy out}}{\text{Energy in}} = 3.5\text{-}3.6$$

Figure 4-1. ENERGY RETURN RATIO FROM UNDERGROUND COAL GASIFICATION EXPERIMENT, HANNA I
(Source: L-6631, L-8520)

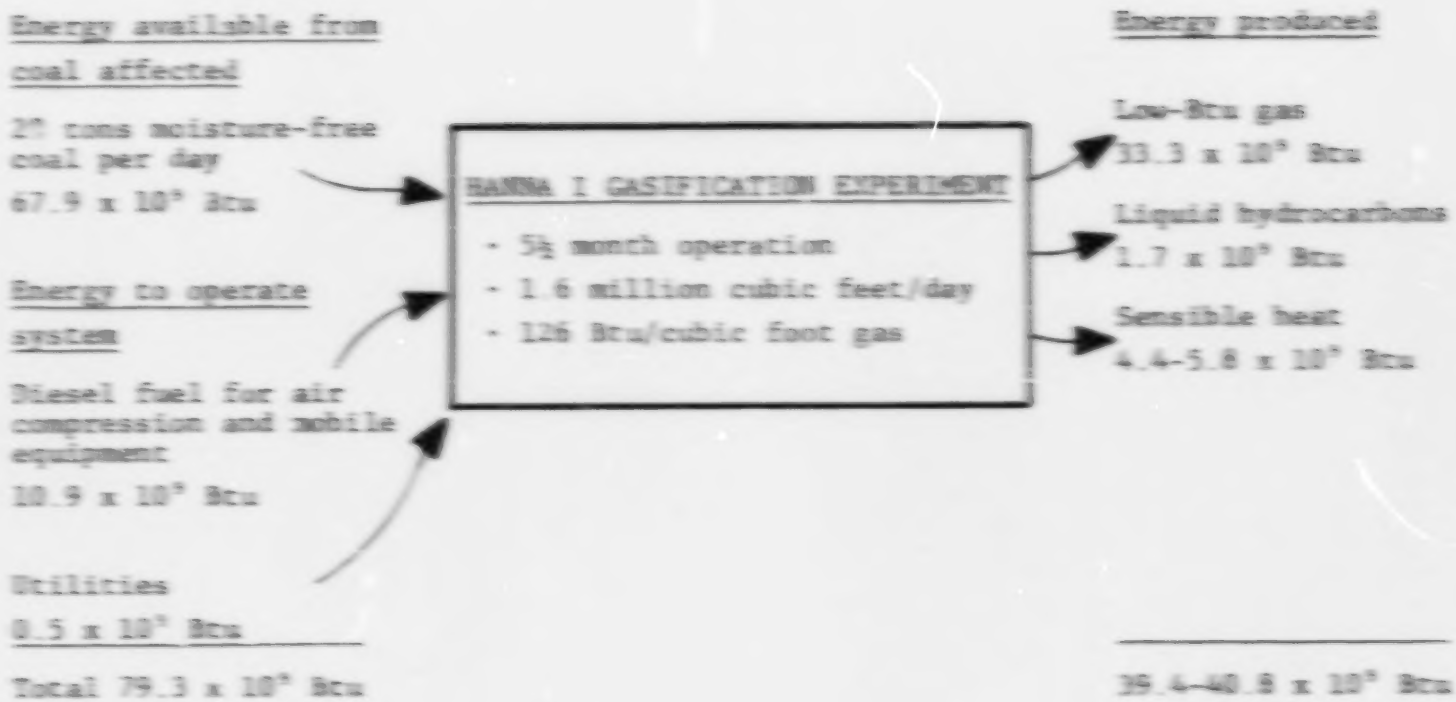
to total energy available to the system; i.e., energy consumed in running the process plus the latent energy available in the amount of coal affected (i.e., gasified or carbonized). Overall energy recovery efficiencies take into account all coal available, not just that affected. Material balance calculations for the Hanna I test indicated that an average of 20 tons of coal (dry basis) were affected daily. This represented an estimated coal utilization of approximately 65 percent. Based on the assumptions employed, the energy recovery efficiency was calculated to be 0.497-0.515 for this case, as illustrated in Figure 4-2. Improved compressors and flare system could possibly result in an efficiency ratio of 0.541-0.560 (L-4822, L-6631).

An overall energy recovery efficiency of 37 percent was reported for the Hanna I test (L-8520). The original literature should be consulted for details of the various calculations. Some discrepancies were noted which were apparently due to different sets of assumptions and calculation techniques applied to the Hanna I test results.

4.3 TECHNOLOGICAL DEVELOPMENT STATUS

In-situ gasification has been developed to commercial scale in several countries outside the U.S., but it is not considered fully developed in this country. A summary of technical research needs for UCG was presented in Section 2.1.3.

Surface coal gasification processes are presently at various stages of development. Numerous small commercial-scale low-Btu gasifiers are presently operating in the U.S.; although several large plants have been proposed, none are yet built. This is not the case in other countries, however, where coal conversion has been more fully utilized. There are still unsolved technological problems with high-Btu processes.



$$\frac{\text{Energy produced}}{\text{Energy used + energy in coal}} = 0.497\text{-}0.515$$

Figure 4-2. ENERGY RECOVERY EFFICIENCY FROM UNDERGROUND COAL GASIFICATION EXPERIMENT, HANNA I

(Source: L-6631)

4.4 ECONOMICS

Only very general comments regarding economic comparisons of in-situ gasification and above-ground gasification can be made at this point. It has been stated that, although it is generally considered economically unfeasible to transport the low-Btu product from remote locations, UCG in general may be cheaper than above-ground processes (L-1326, L-5480, L-8520). In addition the costly transport of coal to the above-ground conversion plant (if not a mine-mouth facility) must be considered.

4.5 LAND USAGE AND IMPACT

This category includes such aspects as land (space) requirements, subsidence and degree of land disturbance or tremors, reclamation requirements, land disposal of wastes, and future land use.

Land area requirements for in-situ gasification will be much less than for a comparable strip mine/surface gasification module as is indicated by the estimated figures presented in Table 4-2. The degree of land disturbance from each case is indicated by the acreage subjected to subsidence (in situ) and stripping (strip mining). Approximately twice as much land will be disturbed by strip mining, and in addition the degree of disturbance is likely to be much greater for this case; only mild subsidence is generally predicted for in-situ gasification although this estimate is unsupported at this time (L-683, L-8520). The exact degree will be a function of many factors such as depth and thickness of seam gasified, quantity of coal blocks left for support, characteristics of overburden, degree of faulting in area, and other geological and hydrological factors. Along a similar line, the impact due to tremors from

Table 4-2. EFFECTS OF UNDERGROUND COAL GASIFICATION COMPARED WITH STRIP MINING PLUS SURFACE GASIFICATION

	Case A Underground coal gasification	Case B Strip mining plus surface gasification
Land area for plant facilities, square meters	81,000	490,000
Stripped land per year, square meters	0	1,000,000
Total land subjected to subsidence per year, square meters	510,000	0
*Water required, cubic meters per year	11,000,000	11,000,000
Sulfur recovered, kg per day (needs to be disposed of if it cannot be sold)	180,000	180,000
Ash to be disposed, kg per day	0	1,800,000

Basis: One plant producing 7 million normal cubic meters (250 million standard cubic feet) of SNG per day; coal containing one percent sulfur and 10 percent ash; 50 percent recovery of coal for Case A with a seam thickness of 15.2 meters (50 feet); 50 percent recovery of coal stripped for Case B with a seam thickness of 7.6 meters (25 feet).

Source: L-681

*This value is based on stoichiometric water requirements and does not include such items as water quality requirements and the potential for utilizing the water present in the coal seam; however, water quality generally does not have to be as high for underground gasification. Also, there will usually be more water available for the underground seam than for above ground.

explosive fracturing during in-situ pregasification has also not been quantified. To date, little evidence of a significant problem has been noted (L-683).

Reclamation of strip-mined land is a massive undertaking. Based on current plans for installation of commercial gasifiers for power generation, all those nearing commitment are located in the western states and will be in conjunction with strip mining. The arid climate in these regions will complicate the reclamation efforts because of the difficulties involved with revegetation (L-683).

Disposal requirements for wastes generated by in-situ processes will be minimal compared to those for a comparable conventional mining/surface gasification case. The only significant wastes from in-situ gasification will be coal tar condensate from the product gas and sulfur recovered during gas purification. Surface processes, on the other hand, have to deal with the additional problems of ash disposal and significant coal mining and preparation wastes. This includes spoil banks, slack piles and tailings ponds (L-1216, L-683).

Future uses which can be made of the land overlying an in-situ gasification site are also undetermined at this time. This may be comparable to that over deep-mined regions. Factors such as seam thickness, depth and nature of overlying rock strata will be involved (L-683). Strip-mined land, on the other hand, can usually be converted to recreational or agricultural purposes after considerable reclamation. Some light building may be possible.

4.6 WATER POLLUTION POTENTIAL

This environmental aspect is the one receiving most attention in UCG investigation. The main area of concern is contamination of groundwater as a result of gas leakage, excursions, and leaching of inorganic ash components and organic coal tars condensed in and around the reaction zone. Coal has been found to have high sorption capacities for many of the potential contaminants. Modeling studies are being conducted to predict dispersion and movement of the groundwater plume. Preliminary results of these studies indicate a low potential for significant groundwater contamination.

The main source of wastewater from surface gasification is ash quenching. This stream can be treated by currently available technology. The magnitude of the water pollution problem from strip mining and deep mining, however, is much greater. This acid mine drainage can be controlled, but application of the technology is difficult because it is an uncontained source.

4.7 AIR POLLUTION POTENTIAL

The potential impact on air quality due to in-situ gasification was summarized in Section 3.2 of this report. In general, a possibility exists for fugitive hydrocarbon and carbon monoxide emissions from coal seam outcrops and high-pressure equipment. Fugitive dust will be generated from on-site vehicular traffic and site preparation activities.

Process emission sources will include gas purification units which should be similar in magnitude and composition to surface low-Btu process emissions. Additional emissions from

surface facilities will include particulates from the coal preparation module and glycol and additional process condensate from the gas up-grading units (high-Btu only).

4.8 HEALTH AND SAFETY ASPECTS

There are many occupational health and safety hazards associated with deep coal mining methods. These include occupational diseases, mine explosions and fires due to high levels of gas and dust, mine collapses and other safety hazards (L-1215, L-1326, L-4822, L-8520). In the case of in-situ coal gasification, worker exposure to all of these problems is avoided. Occupational safety and health aspects of UCG have not yet been investigated, while studies of this type related to above-ground coal conversion have only recently been funded.

APPENDIX A

ERDA'S LINKED VERTICAL WELL PROCESS AT HANNA, WYOMING

The linked vertical well (LVW) concept of in-situ gasification has been under development since 1972 by the Laramie Energy Research Center (LERC). Initial funding was provided by the Bureau of Mines but the program has more recently been carried out under ERDA sponsorship. The objective of this project has been to test the feasibility of UCG in thick (>7.6m or 25 ft), deep (>107m or 350 ft) seams of western subbituminous coal. A secondary objective of tests completed thus far has been to maximize the heating value of the product gas while simultaneously stabilizing the production rate and achieving a high coal utilization efficiency (L-8520).

This process is in the most advanced development stage of any on-going U.S. in-situ gasification project. Two full field test programs have been completed (Hanna I and II) and additional tests are planned. Results of the Hanna II experiment showed greatly improved gas production rates and heating values over earlier phases of the testing. Over a 30-day period an average of 2.2×10^5 Nm^3/day (8.5×10^6 scf/day) of gas rated at $7.12-7.52\times10^6$ J/Nm^3 (175-185 Btu/scf) was produced. This is equivalent to approximately 6 MW of electricity. Future plans include a pilot-scale project (15 MW) to be operational by 1981 (L-9171). Further details of this project are given below.

LVW Process Description

The UCG experiments at the Hanna site are based on the linked vertical well (LVW) technique with air as the oxidizer. LVW is a two-phase procedure for gasification of the coal between two wells in a coal seam in which one well serves as the injection

well for introducing the oxidizer into the coal seam and the other serves as the production well for transport of the product gas to the surface (L-8555, L-8300). Figure A-1 illustrates the LVW concept of in-situ coal gasification.

During the first phase, linkage, a path of increased permeability between the two wells is created by reverse combustion (combustion front propagation countercurrent to injected air movement). Combustion is initiated at the bottom of the production well with an electric heater and moves toward the injection well during a period of low-flow (~0.02 Nm^3/sec or 50 scf/min), high-pressure (~1.8 MPa or 250 psig) air injection. An increase in permeability occurs as the combustion zone nears the injection well allowing injection of larger quantities of air (~0.9 Nm^3/sec or 2000 scf/min) at lower pressure (~0.31-0.45 MPa or 30-50 psig).

At this point the system is prepared for gasification, the second phase of the process. The combustion zone movement is shifted to forward combustion (propagation of the combustion front in the same direction as air injection) while high injection air rates are maintained. The combustion front spreads over a larger area around the injection well and the coal between the two wells is gasified as the front moves toward the production well while producing a low-Btu gas.

Hanna Test Site

Parameters considered in site selection included seam depth and thickness, overburden characteristics, seam water content, coal characteristics and dip. The test site chosen is located approximately 110 km (70 miles) northwest of Laramie near Hanna, Wyoming, as indicated in Figure A-1 (L-8557, L-6631).

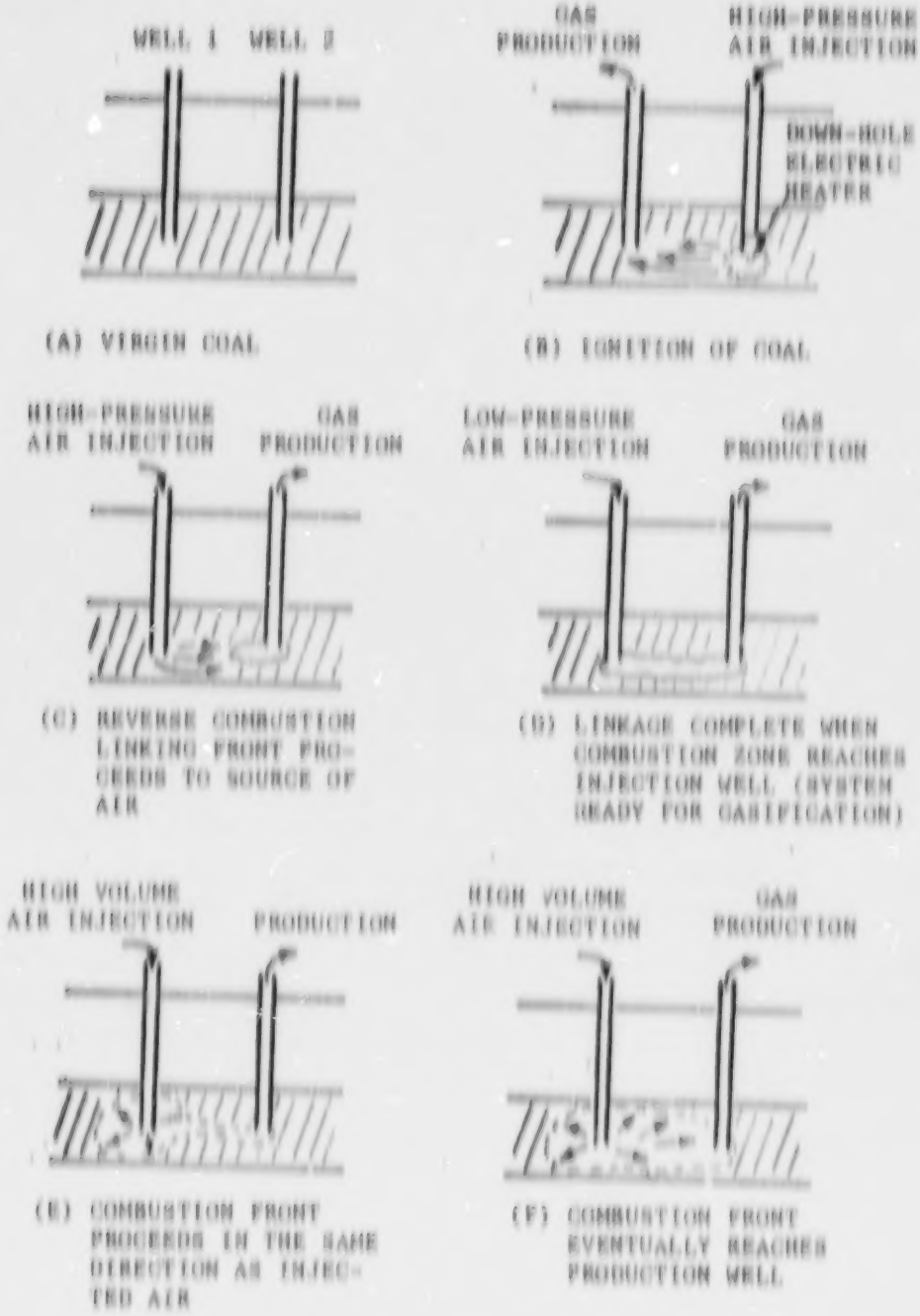


Figure A-1. DIAGRAM OF LINKED VERTICAL WELL CONCEPT OF UCG
(Source: L-8555)

Figure A-2. LOCATION MAP OF LERC UNDERGROUND COAL GASIFICATION EXPERIMENT SITE (Source: L-6631, L-327)

The coal seam being tested is the Hanna No. 1 seam, which is a subbituminous coal, approximately 9m (30 ft) thick, 107-122m (350-400 ft) deep and approximately 55-61m (180-200 ft) below the water table. The seam outcrops on three sides and is isolated on the fourth by faulting. A hydrostatic force of 0.58-0.72 MPa (70-90 psig) is exerted on the gasification zone (L-8557, L-327, L-6921).

The local overburden consists of a series of shales, siltstones and sandstones. Strata directly above and below the coal seam consist of less permeable shales with 4.6m (15 ft) above and 1.2m (4 ft) below the coal. With the presence of an aquifer 24m (80 ft) above the coal seam, as well as the seam itself being saturated, gas leakage has not been a problem. However, influx of seam water in excess of that required by the process as a hydrogen source must be controlled by increased back pressure and increased air injection rates (L-6921, L-8557).

Chemical characterization of coal core samples from two different sites within the Hanna coal field is summarized in Table A-1. Results showed that vertical differences were great and unpredictable, but samples from the same horizontal stratum were systematically and predictably different. In addition, analyses of eight potentially toxic trace elements in coal core samples were also reported and compared to those from an eastern in-situ test site. The Hanna coal contained significantly higher levels of fluorine and lead, while the eastern coal was higher in arsenic and beryllium. Cadmium, mercury, selenium and tellurium were also measured but significant differences were not observed (L-5722).

Table A-1. CHEMICAL COMPOSITION OF SUBBITUMINOUS "A" COAL CORE SAMPLES FROM SITES 1 AND 2 OF THE HANNA COAL FIELD, HANNA, WYOMING

Determination[a]	Drill Hole 3, Site 1 (9 Subsamples)[b]		Drill Hole 3A, Site 1 (21 Subsamples)[c]		Drill Hole 9A, Site 2 (40 Subsamples)[d]	
	Range, %	Average, %[e]	Range, %	Average, %[e]	Range, %	Average, %[e]
Total carbon	37.62 - 69.89	60.69	22.5 - 73.48	54.78	27.5 - 73.1	49.62
Volatiles	23.85 - 43.57	39.79	22.8 - 52.38	37.48	25.6 - 46.8	34.65
High-temperature ash (750°C)	5.62 - 38.89	36.95	3.8 - 38.78	24.48	3.7 - 38.9	32.65
Total sulfur	0.42 - 2.89	0.88	0.3 - 4.28	0.85	0.38 - 2.68	0.75
organic sulfur	0.26 - 0.69	0.47	0 - 0.84	0.38	0.05 - 0.88	0.39
pyritic sulfur	0.02 - 2.24	0.37	0.05 - 3.84	0.43	0.08 - 2.25	0.34
sulfate sulfur	0.02 - 0.25	0.04	0 - 0.39	0.03	0 - 0.43	0.23
Fixed carbon	37.25 - 59.87	43.32	1.3 - 53.38	37.57	5.5 - 52.48	33.69
Hydrogen	2.48 - 5.25	4.39	1.4 - 7.38	4.26	1.6 - 5.48	4.05
Moisture	5.59 - 8.06	7.24	4.3 - 9.9	7.91	5.6 - 10.78	8.62
Nitrogen	0.63 - 1.47	1.35	0.5 - 1.8	1.39	0.48 - 1.88	1.25
Oxygen	7.65 - 26.28	16.88	6.4 - 38.7	13.68	4.28 - 26.48	22.38

[a] The 9 subsamples from Drill Hole 3 were vertical halves of 3-in 3-inch long conservation cores or cuttings collected in the depth range 421.0 - 496.0 ft.

[b] The 18 subsamples from Drill Hole 3A were vertical halves of 4-inch long conservation subsamples taken in the coal interval at 474.0 - 496.0 ft (Results for 3 subsamples in this interval are not reported, due to sampling losses.)

[c] The 40 subsamples from Drill Hole 9A were vertical halves of 3-inch long conservation subsamples taken in the coal interval at 267.5 - 290.5 ft.

[d] All values are on a moisture-free basis.

[e] The average for each determination is a weighted average for the entire coal interval, allowing for differences in thickness of individual coal subsamples.

Source: [illegible]

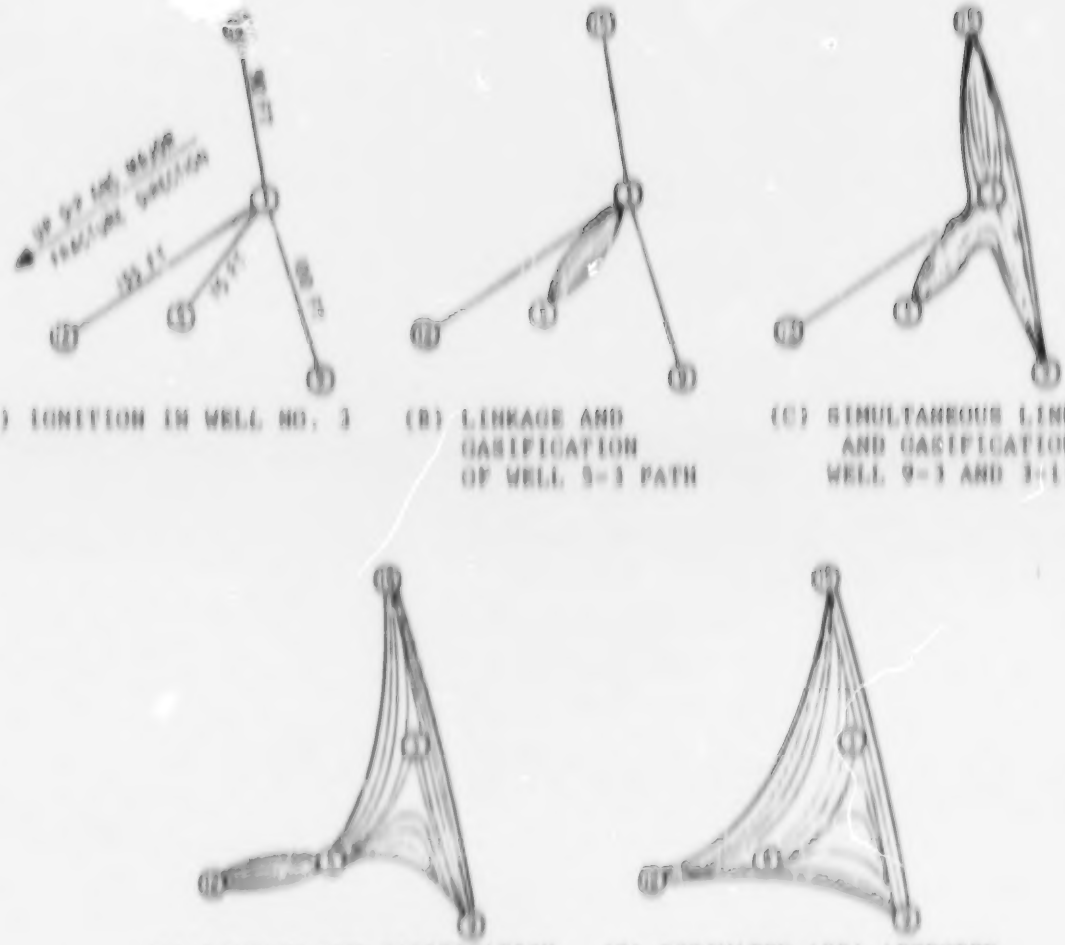
Test Program - Status and Results

Two field test programs, Hanna I and II, have been completed and plans have been finalized for Hanna III and IV. Objectives and approaches are also being outlined for additional tests. Brief descriptions of each experiment are presented below (L-9118).

Hanna I - The first Hanna experiment was initiated in March 1973 and terminated in March 1974. Both forward and reverse combustion techniques using air as the oxygen source were tested. Figure A-3 illustrates the well spacings and sequential linkage pattern.

All linkages started from a common but expanding combustion zone at Well No. 3 which was hydraulically fractured prior to ignition. Attempts to achieve linkage by forward combustion proved unsuccessful due to plugging by carbonization products. Reverse combustion linkage was successfully carried out. This stage was typically characterized by high-pressure air injection (1.8 MPa at 120 m or 250 psig at 400 feet) at a low rate. When the combustion zone reached the injection well, an abrupt pressure drop occurred; at this point larger volumes of air were injected at low pressure (~0.9 Nm^3/sec at 0.31-0.43 MPa or 2000 scfm at 30-50 psig) until linkage was complete. Gasification then proceeded under a forward combustion mode. Approximately three months after air injection was halted, combustion was extinguished by natural influx of seam water (L-327, L-6631, L-8580).

A complete history of gas production rate, air injection rate and Btu value of produced gas is available in the literature (L-8520, L-327, L-748, L-6631). Combustion was maintained continuously over the entire test period. From mid-September through



(A) IGNITION IN WELL NO. 3

(B) LINKAGE AND GASIFICATION OF WELL 5-3 PATH

(C) SIMULTANEOUS LINKAGE AND GASIFICATION OF WELL 9-3 AND 3-13 PATHS

(D) LINKAGE AND GASIFICATION OF WELL 13-5 PATH

(E) ESTIMATED AREA AFFECTED IN HANNA NO. 1 EXPERIMENT

Figure A-3. SEQUENCE OF LINKAGE IN THE HANNA #1 EXPERIMENT
(Source: L-6631)

February 1974, gas production rates and gas heating values stabilized; gas production averaged 4.2×10^5 Nm^3/day (1.6×10^6 scf/day). The average gas heating value was 5.12×10^6 J/Nm^3 (126 Btu/scf). This is equivalent to one MW of electricity at a 40% conversion (thermal) efficiency. A typical analysis of the gas produced is presented in Table A-2. Material balance calculations indicated no gas leakage from the reaction zone, significant influx of groundwater to the reaction zone, consumption of approximately 20 tons of moisture-free coal per day during the stable 5½-month period, and a 63 percent resource utilization. Energy balance calculations indicated that about 3.5 times more energy was produced than consumed during the experiment.

In general the results of the Hanna I experiment showed that groundwater influx and gas leakage can be controlled by air injection pressure. Relatively constant gas production rates and gas heating values were maintained and directional control of the combustion front movement was achieved during the reverse combustion mode. Considerations not addressed in the first test were prevention of roof collapse, maximization of coal utilization, measurement of temperatures within the combustion zone, location of the combustion zone as a function of time, and overall process control (L-1436, L-6631).

<u>Hanna II</u> - The Hanna II test program was a more closely monitored operation which was designed to take advantage of the natural permeability of the coal seam while applying information gained from Hanna I. This experiment was carried out at a location about 240m (800 ft) west of the Hanna I site. The coal seam thickness was the same but it is much closer to the surface at this location (85m or 275 ft compared to 120m or 400 ft at Hanna I). The layout of the four principal wells is shown in

Table 4-2. TYPICAL COMPOSITION OF DRY GAS PRODUCED IN UNDERGROUND COAL GASIFICATION EXPERIMENT, HANNA 1

Constituent	Mole percent
H_2	15.96
Argon	0.76
N_2	53.16
CH_4	3.91
CO	6.33
C_2H_6	0.39
CO_2	19.22
C_3H_8	0.13
C_4H_8	0.04
$i\text{-}C_4H_{10}$	0.01
H_2S	0.07
Heating Value 3.04×10^6 J/Nm^3 (124 Btu/scf)	

Source: L-1382, L-4822

Figure A-4. Stratigraphic correlation of core sample data from these wells indicates a distinct heterogeneity of the seam over distances as short as 18m or 60 ft, thus making modeling of fluid flow in such a complex system very difficult (L-8552, L-6631).

The objectives of Phase I were to evaluate coal seam permeability, investigate pneumatic linking and linking via reverse combustion, and sustain gasification between the two linked vertical wells (L-4674, L-8552). Extensive in-situ and surface instrumentation was installed to provide data needed for further understanding of the process. This phase was conducted from April through August of 1975. The following results were obtained:

- Control of reverse combustion linkage was demonstrated.

- The preferred flow direction was updip and along the general direction of geological fracturing.

- Completion of the wells near the bottom of the seam resulted in placement of the link in the bottom half of the seam, thus preventing passing over the top of unreacted coal (overriding).

- Air injection rate could be reduced by a factor of 10 with only a 20 percent reduction in Btu-value. Less than a 6-hour response time was necessary to return the system to full operating conditions.

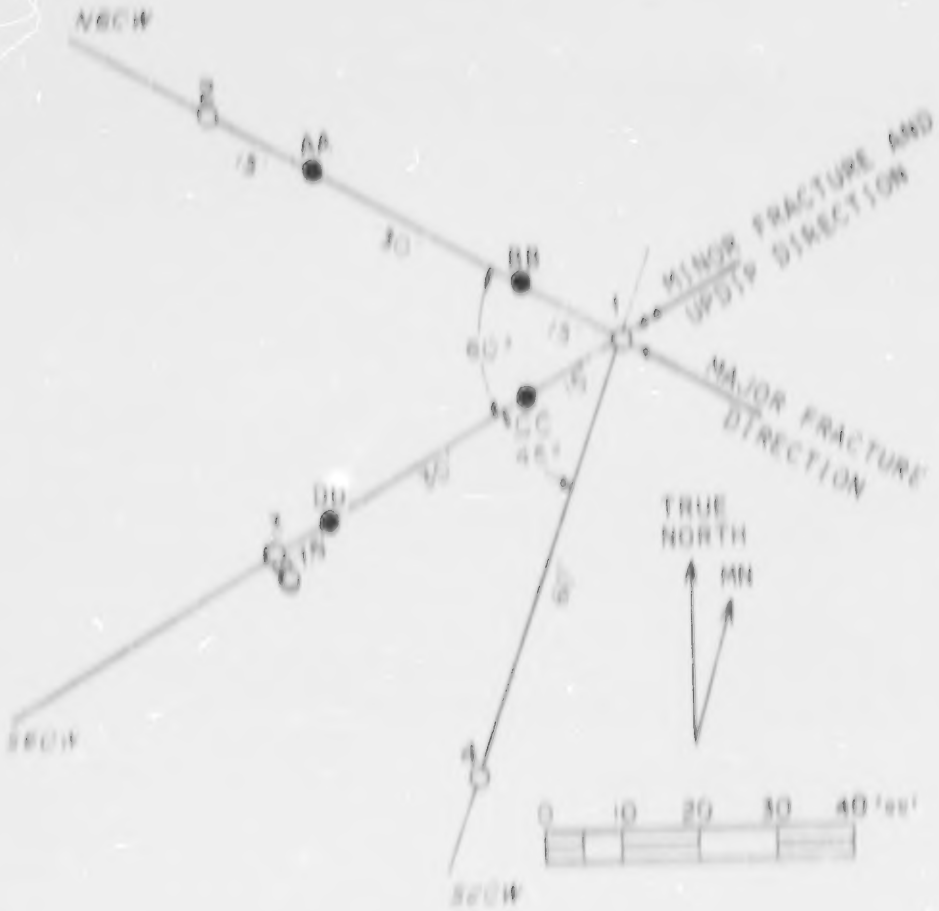


Figure A-4. WELL PATTERN, PHASE I OF THE HANNA II EXPERIMENT
Source: L-4674

Table A-3 gives the overall average composition of product gas from Phase I. A tabulated summary of additional results from Phase I and later phases of Hanna II is presented in Table A-4.

Table A-3. OVERALL AVERAGE COMPOSITION OF PRODUCT GAS FROM HANNA II, PHASE I

Component	Vol %	Component	Vol %
H_2	17.3	N_2	51.0
CO	14.7	Ar	0.6
CO_2	12.4	H_2S	0.1
CH_4	3.3	C_2-C_4	0.6

Source: L-4674

During the experiments, two flares were available for disposal of the low-Btu gas produced, both located approximately 10m (100 yards) from the well site. The small flare had capacity for 2 m^3/sec (4000 cf/min) of production gas for use during the linkage phase and low-flow gasification experiments. The large flare had capacity for ~6 m^3/sec (12,000 cf/min) of production gas for use during high-flow gasification. Only the large flare was equipped with sample ports for sampling of the discharge. Both flares were equipped with forced draft combustion air blowers (L-8300).

Phases II and III of Hanna were designed as four-well experiments as shown in Figure A-5. Wells 5, 6, 7 and 8 were drilled 18m (60 ft) apart in a square pattern. Wells designated by letters were instrument wells, the details of which are summarized in Table A-5. Phase II, completed in May 1976, involved the following steps:

Table A-4. SUMMARY OF HANNA II RESULTS

	Phase		
	I	II	III
Duration	6/4-7/11/75	5/4-31/76	6/24-7/31/76
Well spacing m (ft)	16 (52.5)	18.3 (60)	18.3 (60)
Coal consumption MT in place (tons)	1140 (1260)	1890 (2080)	3100 (3420)
Average heating value 10^3 J/NM^3 (Btu/scf)	6.18 (152)	6.97 (171.4)	5.60 (137.8)
Total air injected 10^6 Nm^3 (10^6 scf)	1.87 (72.2)	2.81 (108.4)	5.47 (210.7)
Total dry gas produced 10^6 Nm^3 (10^6 scf)	2.66 (102.5)	4.47 (172.3)	7.92 (305.4)
Energy Return Ratio	5.2	4.5	4.5
Cold gas thermal efficiency	0.83	0.89	0.77
Overall process efficiency	0.72	0.74	0.65

Source: L-9170

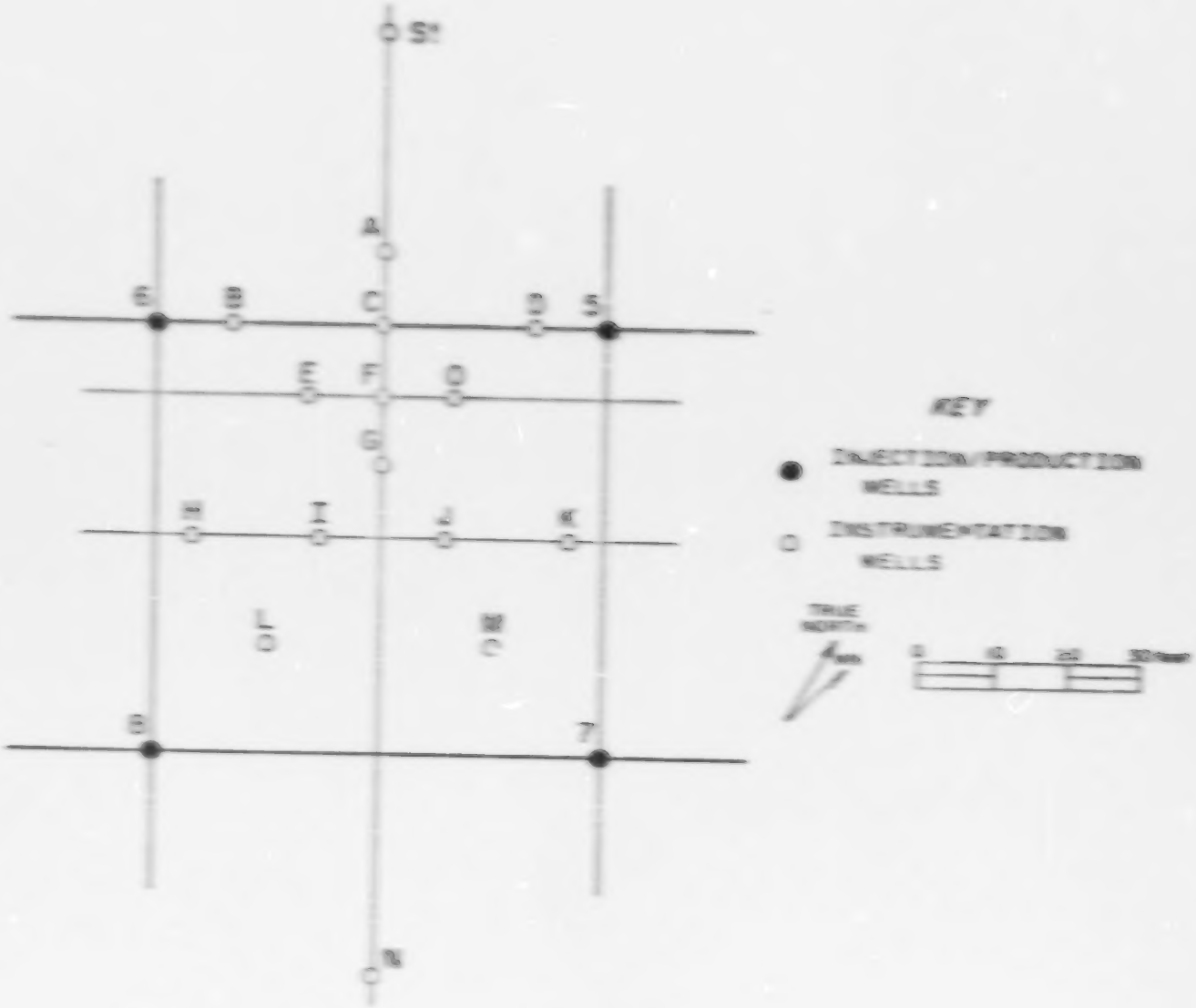


Figure A-5. WELL PATTERN FOR HANNA II, PHASES II AND III
(Source: L-9118)

Table A-5. SUMMARY OF INSTRUMENTATION FIELDED FOR PHASES II AND III OF THE HANNA II UNDERGROUND COAL GASIFICATION EXPERIMENT

Instrumentation Well	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	Total
Low Temperature Levels[1]	10	9	10	10	8	9	9	10	10	10	10	10	10	7	9	141
High Temperature Levels[2]		3	2		3	3										12
Resistivity Probes[3]	3	3	3	3	3[4]	3[4]	3	3	3	3	3	3	3	3	3	48
Geophones	10	10	10	10	10	10	10[5]	10	10	10	10	10	10	10	10	150
Gas Sampling Canisters		1	1	1	1	1	1		1	1					1	9
Absolute Pressure Transducers			1			1	1									3
Surface Pressure Transducers		1	1	1	1	1	1		1	1					1	9
Tilt Meters		2	2			2		2	2	2	2					14
Displacement Levels			4		4		4									12
																198
Plan Surface: Geophone Array (20 ft depth)																15
Resistivity Probe Array																81
															TOTAL	494

[1] Up to six-fold redundancy at most levels plus resistance and noise measurements greatly increase the total number of thermal channels available.

[2] Different materials fielded for evaluation.

[3] These probes also fielded in shut-well. [illegible]

High-temperature sensors and cables fielded in these wells.

[5] Different geophone spacing to measure vertical attenuation.

Source: [illegible]

- Linkage of Wells 7 and 8 by reverse combustion with ignition at Well 7.

- Linkage of Wells 5 and 6 by reverse combustion with ignition at Well 5.

- Gasification in the forward direction between Wells 5 and 6 with injection at Well 6, utilizing three different injection rates 0.74, 1.08, 1.1 Nm^3/sec or (1700, 2500, 3500 scf/min).

The results of this phase showed that a linkage path in a narrow channel could be placed at the bottom of the coal seam. At the midpoint of the 5-6 gasification line there were indications that the reaction front could have been as wide as 18.3 m (60 ft). Results of this 27-day gasification test are summarized in Table A-4. During the planned changes in injection rates no dramatic change in either the gas composition or the heating value occurred. The improved gas quality and resource utilization was attributed to the higher injection rates used and the use of backpressure on the system to maintain the proper air/water ratio.

During Phase III, the line drive portion of Hanna II, the following steps were planned:

- Simultaneous injection into Wells 7 and 8 to achieve a broad reverse combustion linkage between the 5-6 pathway and the 7-8 pathway.

- Gasification of the area encompassed by the four wells by injection into 7 and 8 utilizing 5 and 6 as the production wells.

The attempt to create a broad linkage pathway, however, was unsuccessful. Instead, a narrow link formed close to the line between Wells 6 and 8. Phase III was therefore modified to another two-well burn from 8 to 7 which was completed on July 30, 1976. These results are also summarized in Table A-4. The most significant difference between the results of Phases II and III was the effect of excess water during Phase III. Excess water greatly lowered the heating value of the product gas and the thermal efficiency of the gasification process (L-8552).

The overall accomplishments of the Hanna II experiment can be summarized as follows(L-9118, L-9170):

- Highest gross heating value over the longest duration ever reported
- Highest thermal efficiencies ever reported
- High overall sweep efficiency for parallel two-well gasification systems
- Most thoroughly instrumented UCG test ever conducted
- Highest production rates from any UCG test in the free world
- No measurable gas leakage from the reaction zone during gasification
- First monitoring of product gas stream for trace components.

In summary, the results of eight different reverse combustion linkages at Hanna indicated that "subbituminous coal is ideally suited to reverse combustion linkage both from a controllability standpoint and the quantity of air needed to complete a linkage" (L-8555). Great improvements in the control of gas quality and production rate were achieved during the progressive gasification stages.

Hanna III - The third Hanna test will be conducted during the third quarter of FY 77 at a site approximately 210 m (700 ft) west of the Hanna II site. Site preparation work is now in progress. The primary objective will be to determine the impacts of in-situ gasification on water quality. The well pattern to be used, illustrated in Figure A-6, consists of two process wells on an 18 m (60 ft) spacing and ten water monitoring wells. The coal seam aquifer and any overlying aquifers will be monitored prior to and following the gasification test for a minimum of 18 months. Baseline water quality, flow direction, flow rate, storage coefficients and transmissivity for the aquifers will be established (L-9118).

Additional objectives for Hanna III include demonstrating the feasibility of computer monitoring for process control and demonstrating the stability of product gas composition by maintaining a constant air/water ratio.

Hanna IV - Plans have been finalized for Hanna IV. The objectives are outlined below (L-9170):

- Determine relationships between injection rate, well separation and sweep width

- Determine feasibility of linking over distances of 30 and 45 m (100 and 150 ft)

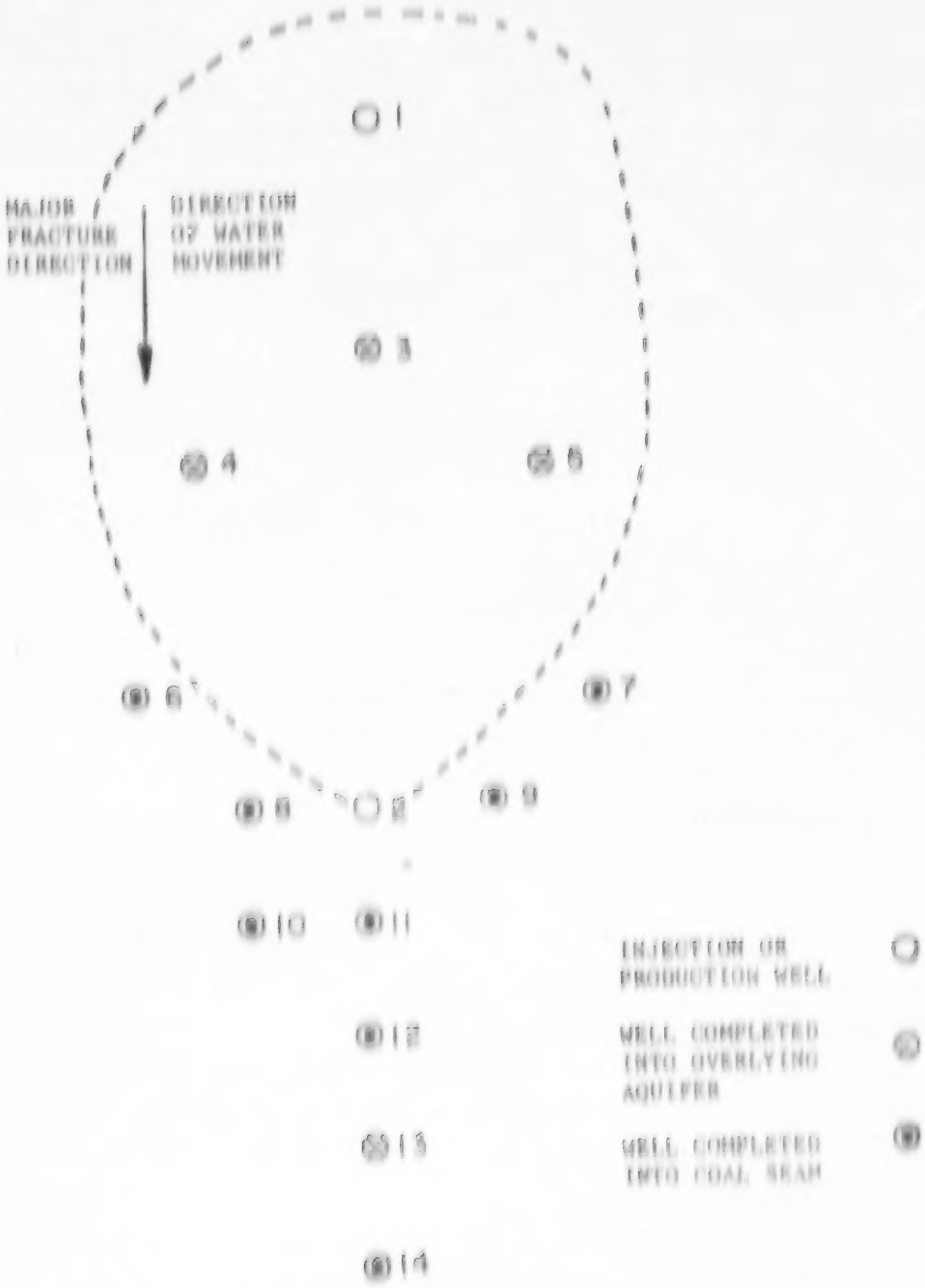


Figure A-6. HANNA III WELL PATTERN
(Source: L-9170)

- Define void shape and gasification front incliration as a function of time

- Demonstrate relaying process from one 2-well system to another

- Determine pressure and gas composition gradients within the seam as a function of time

- Monitor product gas for trace components over total test life

The test setup will consist of 9 wells at 30 and 45m (100 and 150 ft) spacings between pairs (L-9118).

Hanna V - The Hanna V test as presently planned will consist of nine wells in three rows of three wells each. This experiment will be of longer duration (12 months) with production rates up to 2.3×10^5 Nm^3/day (9.0×10^7 scf/day). Gas turbine and gas cleanup testing may also be conducted. A summary of the objectives for this test is as follows (L-9170):

- Demonstrate simultaneous operation of multi-well pattern

- Determine impacts of subsidence on process

- Demonstrate process control with in downhole instrumentation

- Demonstrate feasibility of product gas cleanup and utilization

- Obtain design information for scale-up to demonstration plant

- Obtain final test information for economic analyses

Water Quality Studies

An investigation of potential groundwater pollutants produced during in-situ gasification is underway by researchers at the Laramie Energy Research Center. Coal tars which are generated during gasification processes are known to contain phenols, pyridines, anilines, quinolines and aromatic hydrocarbons. All but the phenols are relatively insoluble in groundwater. Coal itself may sorb some soluble organic components. These phenomena may minimize dispersion of organic contaminants and thereby limit their impact. On the other hand, inorganic residues in the ash or char may be more accessible for dissolution in the groundwater system (L-8520).

To date most characterization work has been carried out on coal tar condensate samples collected during the Hanna I experiment (L-748). The two-phase condensate consists of approximately 90 percent water and the remaining 10 percent an organic coal tar layer. The total sample was collected in an air-cooled condenser upstream of the product gas flare. Two samples representing different reaction conditions were taken for characterization: one during a period of low gas production associated with carbonization (linkage phase) and the second during a high gas production period associated with gasification. The organic (tar) fractions were subjected to fractionalization schemes and subsequent analyses.

Many coal tar samples collected during numerous gasification tests at Hanna have been physically characterized. The results for three selected parameters for samples collected during gasification and carbonization periods are presented below (L-748).

	Sample 1 (carbonization)	Sample 2 (gasification)
Specific gravity at 15°C (60°F)	0.962	0.977
Viscosity at 38°C (100°F) m^2/sec	3.55×10^{-5}	1.316×10^{-3}
Heat of combustion, J/g	3.7383×10^7	4.0134×10^7
(Btu/lb)	(16,073)	(17,256)

In general, chemical characterization of the coal tar samples investigated indicate that tars generated during in-situ gasification differ from those produced during conventional coking operations, primarily in their lack of heavy ends (L-8580). Simulated distillations of the coal tar sample collected during the Hanna I test indicated that none of the material boils above 510°C (950°F) compared to 24 weight percent of a tar produced under laboratory carbonization conditions boiling above 538°C (1000°F). The likely explanation for this is that the higher boiling components of UCG coal tar are separated out during their passage through the coal seam to the surface (L-8580).

A typical elemental analysis of a UCG coal tar is presented in Table A-6. In general the composition of tars has been found to remain relatively constant during a given test at Hanna and from test to test as well. Maximum values measured for nitrogen and sulfur are 1 and 0.5 percent, respectively (L-8580).

Table A-6. TYPICAL ELEMENTAL ANALYSIS OF COAL TAR

Element	Weight percent
C	86.33
H	10.43
N	0.79
S	0.18
O*	2.27

** Percentage determined by difference.*

Source: L-8580

Strong, weak and very weak bases are defined by their half neutralization potential (HNP). Very strong bases have an HNP less than 150 mV, while HNP's of weak bases such as pyridines and quinolines range between 150 and 350 mV. Very weak bases have an HNP greater than 350 mV; examples of these are amides. Primary and secondary anilines will also titrate as very weak bases since they undergo acetylation to amides. Nonaqueous titration of the Hanna I samples produced results shown in Table A-7. Results of total sulfur and total nitrogen titrations are also available in this table.

The intial separation scheme based on mineral acid and sodium hydroxide extractions followed by regeneration via pH adjustment yields three major fractions (L-748):

- Tar acids
- Tar bases
- Neutral oil fraction

Table A-7. TOTAL NITROGEN, TOTAL SULFUR AND TITRATABLE NITROGEN FOR ACID, BASE AND NEUTRAL FRACTIONS OF UCG COAL TAR

	Total sulfur (%)	Total nitrogen (%)	Titratable nitrogen*
Carbonization Sample			
Tar base	0.00	0.04	0.10% WB, 1.35% VWB
Tar acid	0.33	0.35	0.26% WB, .081% VWB
Neutral	0.02	0.08	0.035% VWA
Gasification Sample			
Tar base	0.23	4.82	4.45% WB, 0.36% VWB
Tar acid	0.14	0.09	0.058% VWB
Neutral	0.20	0.32	0.37% WB, 0.145% VWB

* WB and VWB refer to weak and very weak base.
Source: L-748

A slightly modified scheme was described in a later paper (L-8580). The neutral fraction is subsequently separated with aliphatic and aromatic fractions with silica gel, using hexane to elute the aliphatics and methanol the aromatics (L-8580).

The compositional ranges given in Table A-8 were obtained upon fractionalization of numerous tar samples. It was pointed out that the 70:30 ratio of aromatic to aliphatic content of the neutrals fraction was fairly constant over a wide range of samples. The higher oxygen content of the carbonization sample is due to the greater level of tar acids (substituted phenols) present. Results of characterization of the tar base fraction were presented in one paper (L-748), while the weak acids and aliphatics are the subjects of a paper to be presented in the near future (L-8580). These results are summarized below.

Table A-8. COMPOSITIONAL RANGES OF UCG COAL TARS

Fraction	Composition, wt. percent	
	Gasification sample	Carbonization sample
Tar bases	2.5-8.0	4.0
Tar acids:		42.1
Strong acids	0.1-1	
Weak acids	12-31	
Neutrals*	55-77	53.9

* Percentage ratio of aromatics to aliphatics usually constant 70:30.
Source: L-8580

Characterization of Weak Acids - The weak acid fraction of the Hanna I sample (14.3 weight percent weak acids) was found to be almost exclusively phenolic in nature. Specific compounds identified by GC-MS include

- phenol
- p-cresol
- o-cresol
- m-cresol
- 4 different xylenols
- 7 C_3-phenols
- 5 C_4-phenols
- Small amount of aromatic aldehyde or ketone

In addition, H^1 and C^{13}-NMR analyses of manually trapped GLC peaks supported the GC-MS results.

Characterization of Aliphatic Neutrals - This fraction contains a normal saturate series running from C_{13} to

C_{17} with some branched saturates and a particularly heavy level of C_{15} branched saturates. Very limited degrees of unsaturation or cyclic compounds were evident. Specific components identified by GC-MS are listed in Table A-9.

Table A-9. COMPOSITION OF ALIPHATICS FRACTION OF HANNA I COAL TAR SAMPLE

n-C_{15} through n-C_{22} series

Branched saturates:

- 2,11-dimethyl tricosane ($C_{25}H_{52}$)
- 2-methyl tetradecane ($C_{15}H_{32}$)
- 4,11-dimethyl pentadecane ($C_{17}H_{36}$)
- 6-methyl octadecane ($C_{19}H_{40}$)
- 7-methyl octadecane ($C_{19}H_{40}$)
- 3-methyl octadecane ($C_{19}H_{40}$)
- 3,6-dimethyl heptadecane ($C_{19}H_{40}$)
- two polybranched $C_{19}H_{40}$
- 2,4-dimethyl octadecane ($C_{20}H_{42}$)

Source: L-8580

Characterization of Tar Base Fraction - GLC traces for the tar base fractions of both Hanna samples were presented in the literature. Identification of the peaks from the carbonization base was made with the aid of NMR, MS, UV and GLC data. The results tabulated in Table A-10 show that 46.6 percent of the base fraction was substituted pyridines, 13.4 percent anilines, and 9.1 percent quinolines. Most of the remainder was thought to be substituted pyridines.

Table A-10. TABULATED SPECTRA ON SEPARATED COMPONENTS FROM TAR BASE FRACTION OF HANNA CARBONIZATION SAMPLE

Component	t_r *	% Total of base fraction	Compound type or compound
1	8.9	1.18	pyridine
2	11.0	6.40	2-picoline
3	13.1	6.20	2,6-lutidine
4	14.9	9.61	3-picoline, 4-picoline and 2-ethyl pyridine
5	17.3	12.90	2,4-lutidine, 2,5-lutidine plus some methyl ethyl pyridine
6	18.3	3.22	2,3-lutidine
7	19.2	7.11	trimethyl pyridine and an ethyl pyridine
8	31.1	5.98	aniline
9	34.7	4.88	2-methylaniline
10	34.1	2.54	a dimethyl aniline and an ethylaniline
11	39.1	4.08	quinoline, a dimethyl aniline and a trimethyl aniline
12	40.5	5.02	a methyl quinoline, a C_3 aniline; quinoline, a dimethylquinoline

* GLC retention times are relative to air.

Source: L-748

Analysis of the Hanna gasification base sample produced similar results except that the majority of the fraction was heavier than the carbonization sample.

The aqueous fraction of the original condensate samples and some additional water samples from the site tests are currently being analyzed by the Research Triangle Institute. These results are not yet available.

Future water quality studies are planned as an integral part of the Hanna III experiment. To date, no general conclusions have been reached regarding the impact of in-situ gasification on water quality.

Air Quality Studies at Hanna

Product gas and flare discharge resulting from product gas combustion were characterized during Phase II of the Hanna II test of the Linked Vertical Well concept from 19 April through 17 May 1976 (L-8554, L-8300). The product gas was monitored over seven different periods under three different conditions of air injection rate. During each of these periods the product gas was characterized with respect to particulate concentration, size distribution and composition; four minor gas components -- carbon disulfide, carbonyl sulfide, ammonia and hydrogen cyanide; and vapor phase concentrations of ten elements -- sodium, potassium, lithium, calcium, vanadium, mercury, arsenic, lead, selenium and cadmium. Two monitoring periods were performed for the flare discharge during which the discharge gas was characterized with respect to particulate concentration and size distribution, sulfur oxides, nitrogen oxides and total hydrocarbons. Details of this study are available in a recently published report by Radian Corporation (L-8300).

The particulate size distribution of the production gas was determined with Andersen cascade impactor samplers. In general, a trend is evident from the data indicating an increase in total particulate loading and a shift toward larger size particles as the burn progresses. The increase in particulate concentration is particularly apparent between the first three periods when the injection rate was ~0.74 Nm^3/sec (1700 scf/min) and at the higher injection rates. From the data available, it is not evident whether this increase is the result of increasing gas velocities in the system as injection flow was increased or a result of decreasing distance from the combustion zone to the production well. One abnormally high particulate loading was measured on one of the sampling days. The origin of the phenomenon was not known.

Particulate matter entrained in the product gas stream was collected for characterization during each sampling period using a heated cyclone-filter assembly. Materials were also recovered from the extension pipe on the product gas sampling assembly following the final period. This material formed two samples: "large wellhead particulates" which consisted of loose material in the pipe which resembled unreacted coal in appearance and "wellhead scrapings" which were removed from the interior wall of the extension pipe and appeared to be condensed coal tars and adhered fine particulates. Particulate samples were characterized by analysis of major components, semiquantitative spark source-mass spectrometry survey analysis, oil and tar content by extraction with Freon, ash content and determination of bulk density.

The results of analyses of four particulate samples for nine major elemental components after extraction of condensed oils and tars are listed in Table A-11. This list includes the

Table A-11. CONCENTRATIONS OF MAJOR COMPONENTS IN WELLHEAD PARTICULATES[1]

Element	Large wellhead particulates	Wellhead scrapings	Cyclone particulates Run 3 5/5/76 (126)	Cyclone particulates Run 7 5/16/76 (136)
Na	.162	.131	.102	.178
K	.428	.320	.031	.270
Li	–	–	22.1 ppm	36.8 ppm
Ca	3.38	1.24	3.00	.880
Mg	.408	.588	.131	.780
Al	4.85	3.56	.420	3.34
Fe	1.46	2.26	3.38	1.75
Ti	.182	.064	.170	.201
Si	10.4	7.04	1.79	6.10
Oils & tars[2]	1.67	13.2	5.3	1.00

[1] Concentrations expressed as percent in particulate following Freon extraction unless specified otherwise.

[2] Determined by loss with Freon extraction.

Source: [illegible]

elements whose oxides are the major constituents of coal ash. In Table A-12 the concentrations are shown following mathematical conversion to the oxide forms, as is commonly done in mineral analyses of coal ash, and correction for the weight of extracted oils and tars. The total oxides content should approximately equal the ash content of the particulates. As a check, the ash content of the "large wellhead particulates" and the "wellhead scrapings" was determined by combustion. The carbon, hydrogen and oxygen contents were also determined providing analyses of essentially all of the major particulate components. The deviation of the sum of all of these major components from 100% is a measure of the overall accuracy of the analyses.

The concentrations of four gas components (ammonia, hydrogen cyanide, carbonyl sulfide and carbon disulfide) in the product gas were determined during each of the seven complete sampling periods. The results of these determinations are presented in Table A-13. During collection of the samples for determination of these components, significant quantities of condensed oils and tars were trapped in the impinger solutions. Checks for interferences from these condensates in the analyses were made. Details are available in the study report.

The vapor phase concentrations of ten elements in the product gas were also determined via analysis of acidic and basic impinger solutions. The results are presented in Table A-14.

The discharge gas from the flare was characterized on two different sampling days. Tables A-15 and A-16 provide the results of the characterization for particulate concentration size distribution, and concentrations of SO_2, NO_x, total hydrocarbons and major components.

Table A-12. COMPOSITION OF WELLHEAD PARTICULATES

	Large wellhead particulates, %	Wellhead scrapings, %	Cyclone particulates, %		
			Run 3 5/5/76 (126)	Run 5 5/11/76 (131)	Run 7 5/15/76 (136)
Na_2O	.21	.176	.137	-	.240
K_2O	.516	.386	.037	-	.325
Li_2O	-	-	-	-	-
CaO	4.72	1.73	4.19	-	1.23
MgO	.676	.975	.717	-	1.29
Al_2O_3	10.3	7.56	.89	-	7.10
Fe_2O_3	2.09	3.23	4.83	-	2.50
TiO_2	.303	.107	.284	-	.335
SiO_2	22.24	15.06	3.83	-	13.05
Total oxides*	40.38	25.38	13.66	-	25.81
C	41.95	55.69	78.72	60.33	58.06
H	3.29	4.71	6.47	1.01	3.26
O	12.42	13.67	7.87	2.62	11.08
Ash	43.7	24.3			
Total ash + CHO	101.4	98.4	106.72	-	98.21

* Percent values corrected to pre-extracted weights.
Total oxides should approximately equal ash content.

Source: 1-4380

Table A-13. AMMONIA, HYDROGEN CYANIDE, CARBONYL SULFIDE AND CARBON DISULFIDE CONCENTRATIONS* IN THE PRODUCTION GAS

Run	Date (days)	NH_3 %	HCN ppm	COS ppm	CS_2 ppm
1	4/26 (117)	0.22	<1.2	1.1	1.1
2	5/2 (123)	0.13	1.0	3.0	4.7
3	5/4 (125)	0.14	10.0	2.8	2.2
4	5/8 (129)	0.21	9.4	1.7	9.0
5	5/10 (131)	0.28	0.17	0.57	9.8
6	5/13 (134)	0.18	6.9	1.5	7.4
7	5/15 (136)	0.14	0.43	1.1	8.9

* All concentrations are v/v on a dry gas basis.

Source: 1-8300

Table A-14. VAPOR PHASE ELEMENTAL CONCENTRATIONS* IN UCG PRODUCTION GAS

Element	Sampling period and date						
	#1 4/26	#2 5/2	#3 5/4	#4 5/8	#5 5/10	#6 5/13	#7 5/15
Na	4.00	.92	3.97	12.9	.49	4.35	<.05
K	.175	.164	.098	.037	.121	.048	<.02
Li	<.06	<.06	<.06	<.06	<.06	<.06	<.06
Ca	.39	.43	.84	.48	.80	.42	.37
V	.083	.034	.097	.071	.064	.063	.064
Hg	‡	.0099	.0035	.0105	.0102	.0048	.0056
Pb	.039	.012	.030	.033	.021	.016	.011
Cd	.00092	.00054	.00047	.00022	.000095	.000083	.00040
As	.0100	.0066	.0117	.036	.088	.075	.029
Se	.0325	.0355	.0137	.0101	.0186	.0156	.0169

* All concentrations ppm (v/v) on a moisture-free basis.

‡ Insufficient data.

Source: 1-4300

Table A-15. PARTICULATE CONCENTRATION AND DISTRIBUTION IN FLARE DISCHARGE GAS

Size range, μ	Particulate concentration g/10⁶ Nm³ May 6	May 7
>10	6.52	2.55
10-7.0	2.35	1.72
7.0-5.0	2.65	1.42
5.0-3.0	1.95	2.25
3.0-1.0	2.85	5.72
1.0-0.75	1.45	2.07
0.75-0.50	1.80	3.22
<0.50	19.48	23.36
TOTAL	39.05	42.31

Source: L-8300

Table A-16. COMPOSITION OF FLARE DISCHARGE GAS

Component	Concentration* May 6	May 7
Total Hydrocarbons	1480 ppm	920 ppm
Sulfur Dioxide	425 ppm	554 ppm
Nitrogen Oxides	370 ppm	353 ppm
Hydrogen	280 ppm	220 ppm
Nitrogen	76.53%	77.51%
Oxygen	2.14%	4.69%
Argon	1.00%	0.99%
Carbon Monoxide	3.48%	2.42%
Methane	1250 ppm	810 ppm
Carbon Dioxide	16.53%	14.02%
$C_2 + C_3$	820 ppm	30 ppm

* All concentrations are on v/v dry gas basis.

Source: L-8300

Atmospheric emissions from an in-situ gasification module and other energy conversion processes were estimated in another Radian study (L-5480). The basis of the model was as follows:

10^5 Nm^3/day ($4x10^6$ scf/day)
10^{12} J/day (10^9 Btu/day)
10^7 J/Nm^3 (250 Btu/scf)

The only gas treatment assumed was separation of coal tar products. It was anticipated that the only significant emissions from in-situ gasification would be from high-pressure equipment and vehicle traffic around the surface facilities.

An emission factor for fugitive emissions from high-pressure equipment could not be derived from Hanna data because of large leakages due to inadequate well seals at the time the data were reported. Therefore a total environmental emission of 0.22 volume percent of fuel gas produced (based on a previously reported value for miscellaneous hydrocarbon emissions from gas wells) was assumed. Applying this to an available fuel gas analysis the following fugitive emission rates were derived:

Carbon monoxide 13.6 kg/day (30.0 lb/day)
Hydrocarbons (CH_4) 29.5 kg/day (65.0 lb/day)

The emission rate for particulates of 2.5 kg/day (5.5 lb/day) represents fugitive dust from vehicular traffic based on 8 km (5 miles) of unpaved roads with 80 vehicle-kilometers (50 vehicle-miles) daily.

APPENDIX B

ERDA/LLL IN-SITU COAL GASIFICATION PROGRAM

The Lawrence Livermore Laboratory in-situ gasification program was initiated in 1972. Initial funding was provided by the U. S. Atomic Energy Commission during 1972 and 1973. Ongoing work is continuing under ERDA sponsorship (Contract No. W-7405-Eng-48). The LLL process is based on an underground packed-bed reactor model and is applicable to the production of pipeline-quality gas from thick (i.e., 15 meters) seams 150-1000 meters deep. LLL's approach involves:

- Development of mathemacical models of reaction chamber kinetics
- Bench-scale testing
- Small-scale explosive fracturing tests at Kemmerer, Wyoming
- Larger scale field tests at the Hoe Creek site near Gillette, Wyoming

The current development status of the project has been described as still little more than conceptual. Application has been made to the Bureau of Land Management for a Special Land Use Permit to conduct UCG experiments on an 80-acre tract of public land. Under a previous permit, LLL carried out extensive drilling and geological and hydrogeological testing. The goals and current status of the LLL test work are presented in more detail below (L-8544).

In conjunction with this project two different feasibility studies were sponsored by ERDA and LLL. Gulf Research and Development Company and a consortium of companies headed by

Resource Sciences Corporation has evaluated the commercial potential of the LLL packed-bed concept, examined coal availability, and recommended an R&D program leading to a demonstration of the process. The conclusions of both studies were favorable. Namely, more than 100 billion tons of deep, thick, western coal are available; the cost of the resulting pipeline-quality gas would be 60-70 percent of that produced by Lurgi technology, assuming a reasonable sweep efficiency (70 percent) and moderate explosive requirements. It was also concluded that less severe environmental consequences would result from LLL's process.

LLL Process Description

The basic features of LLL's underground packed-bed reactor process are (L-8581):

- Drilling and explosive fracturing of the coal
- Dewatering
- Igniting the top of the permeable fractured area
- Gasification in a downward direction via injection of steam and oxygen
- Surface cleanup and upgrading of the raw gas to high-Btu, pipeline-quality gas

The concept is illustrated in Figure B-1 for a model site. A block diagram is presented in Figure B-2 showing the basic units proposed in the process. Gas purification modules are shown although optimistic reports state that not all of these modules will be needed if sulfur removal and methanation are maximized underground (L-1326).

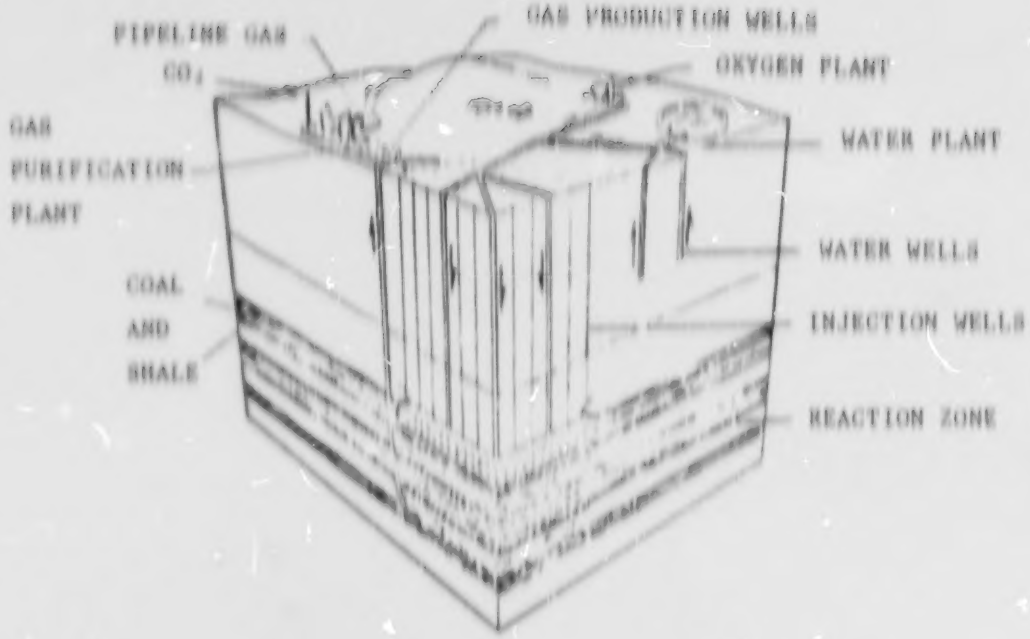


Figure B-1. LLL IN-SITU COAL GASIFICATION CONCEPT
(Source: L-8558)

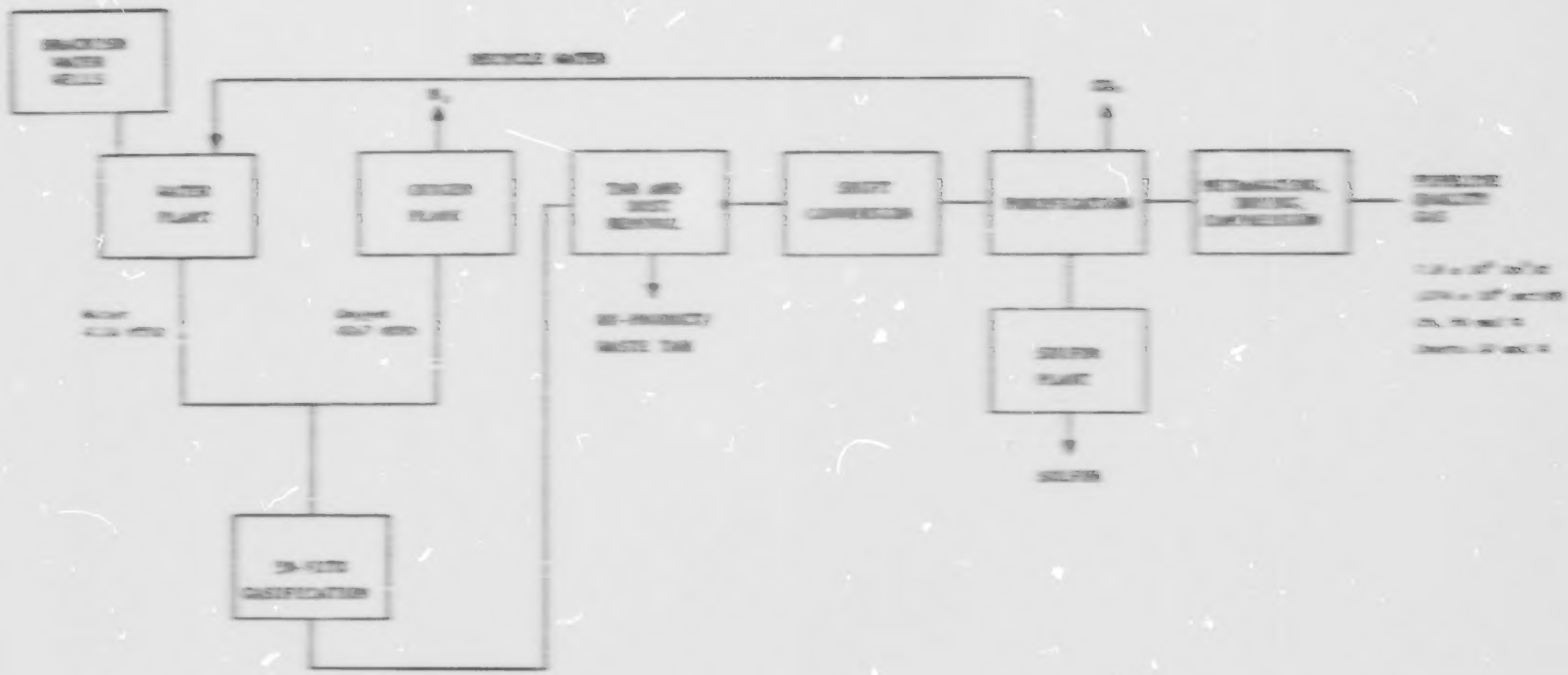


Figure B-2: BLOCK DIAGRAM OF LLL IN-SITU COAL GASIFICATION PROCESS
(Source: L-8558, L-683)

Fracturing - Fracturing is accomplished by means of conventional explosives detonated in an array of drilled holes. Injection and collection wells are then drilled and cased to prevent water intrusion. The collection wells are drilled to the bottom of the reaction zone while the injection wells reach just to the top (L-1326).

Dewatering - Prior to and during gasification, dewatering operations are necessary to remove and then to prevent re-entry of groundwater into the reaction zone. Plans for this operation are not yet definite; however, it appears that this water may be suitable even for livestock use; arrangements were made with a nearby ranch to pipe pregasification water from the first Hoe Creek experiment overland to a stock pond. Water pumped out during gasification will be monitored for possible contaminants (phenols, inorganics, e.g.) and, if necessary, reinjected into the Felix coal formation.

Ignition - In the LLL process the coal at the top of the seam is ignited by injection of oxygen (L-8558).

Gasification - After good combustion is established, oxygen and steam or brackish water is injected. Gasification occurs in a downward direction under operating pressures ranging from 3.5 to 7 MPa (500-1000 psi). This direction reportedly provides more stable conditions because rapid reactions which take place in hot spots are slowed by the buoyancy of the hot gases. The product gas is withdrawn by collection wells drilled to the bottom of the zone. It is desirable to confine the gasification process to specific zones, leaving some coal between zones for support (L-683).

Under oxygen-blown conditions, the product gas is expected to contain principally methane and CO with lesser amounts

of CO_2 and H_2; H_2S will also be present to some extent. A comparison of expected gas compositions from Hoe Creek Test 1 (air) and later tests with oxygen is presented in Table B-1. After gas purification, Figure B-2, the methane content may be as high as 90%. Since the LLL process is aimed at high-Btu gas production, maximum in-situ methanation is desirable. At temperatures above 800°C methanation is equilibrium-limited. At lower temperatures the uncatalyzed reaction proceeds slowly. It is anticipated that methanation will approach completion because of the following factors:

- High pressure
- Long gas residence time in the high-temperature reaction zone (~1 hour)
- Catalytic action of ash and shale

Laboratory data have reportedly yielded supporting evidence. A potential problem may exist, however, due to difficulties in obtaining adequate temperature control because of either in-situ or injected water (L-8558, L-683).

Surface Processing - Since it is anticipated that sulfur cleanup will be accomplished in situ via chemical action of shale, no above-ground sulfur removal facilities are planned. This seems optimistic, however, when considering that 97 percent underground sulfur removal must be achieved in order to meet proposed new source performance standards for fossil fuel conversion facilities, assuming 1 percent sulfur content in the coal (L-683). Other surface facility requirements may include oxygen and steam plants and possibly water treatment units.

Table B-1. GAS COMPOSITIONS EXPECTED FROM HOE CREEK EXPERIMENTS NOS. 1 (AIR-BLOWN) and 2 (OXYGEN-BLOWN)

Test	Gas component	Volume, % (water-free basis) air-blown	oxygen-blown[1]
Gas Composition	H_2	16-17	19.2
	CO	21-23	32.4
	CO_2	5-7	20.4
	CH_4	1.5-2.5	27.0
	H_2S[2]	<0.1	0.5
	N_2	56.5-50.4	0.5
Heating Value		5.3×10^6 J/Nm³ (130 Btu/scf)	3.8×10^7 J/Nm³ (945 Btu/scf)

[1] *Composition corresponds to gases in equilibrium at ~825°C and a pressure of 7.1 MPa (70 atm) and is somewhat higher in CH_4 than Lurgi gasifier products.*

[2] *This is a maximum value and assumes all the sulfur in the coal to be released in the form of H_2S.*

Source: L-8581, L-8582, L-1125

Scope of Work and Project Status

The LLL project involves theoretical, laboratory and field studies. Field studies are being conducted at both the Kemmerer and Gillette, Wyoming, sites. The status in each of these areas is presented below. The main thrust of the environmental assessment studies conducted to date has involved modeling and laboratory studies.

Fundamental Laboratory Studies -

Bench-scale and coal gasification experiments have been conducted in 0.3- and 1.5-m (1- and 5-ft) long packed-bed reactors using steam and oxygen reactants. The gas quality achieved is comparable to that produced in Lurgi gasification processes (L-8558).

Laboratory studies have also been performed to measure the progress of thermal waves. The results were compared to modeling predictions. It was found that Wyoming subbituminous coals shrink upon heating and their permeabilities increase by several orders of magnitude (L-8581).

Water Quality Studies -

LLL's approach to groundwater pollution assessment involves development of a pollutant transport and dispersion model, determination of pollutant parameters and model inputs via laboratory and field studies, and predictive studies using the model. Preliminary results of the modeling and laboratory investigations have been published. No field study data regarding groundwater effects (other than base-line hydrogeological descriptions) are available (L-8581). The status of each task in the water quality program is described as follows.

Pollutant Transport and Dispersion Model Development - A computer model has been developed to calculate transport and dispersion of groundwater pollutants from in-situ gasification processes. Based on a mathematical model developed elsewhere (Holly, et al., Teledyne Isotopes, Nevada Operations), the model describes the hydrodynamic transport of radio-nuclides in porous media. Dispersion and sorption of the pollutants as well as different boundary conditions for release of contaminants into the environment are accounted for.

The transport model is intended to describe the movement of the groundwater plume from the burned-out area. This area will contain primarily ash surrounded by a char ring where heat has pyrolyzed the coal but the char has not gasified. Outside the char ring is a zone contaminated by gases and tars which have migrated from the reaction zone during gasification.

The data input requirements to be supplied from laboratory and field studies include the following:

- Identity and concentration of pollutants
- Size and pollutant source
- Rate of change of pollution source concentration with time
- Groundwater flow velocity and direction
- Sorptive properties of porous media

Laboratory Experiments - Laboratory experiments are being designed and carried out to determine the leachability of inorganic and organic species from the gasification residue and the sorption properties of coal for these potential groundwater contaminants.

The origin of inorganic groundwater pollutants is assumed to be the ash. In one experiment 10-11 gram samples of coal ash obtained by gasifying coal at 1273°K were subjected to leaching with 25-mℓ aliquots of deionized water at flow rates of 17 mℓ/h. The leachates were then analyzed for aluminum, calcium, hydroxide and pH. Thiocyanates and cyanates will also be considered in future tests. Results were expressed in terms of the volume of water required to leach "clean"* one gram of ash and 3.3×10^7 kg of ash (the amount of ash calculated to be present after the Hoe Creek burn); the time required for leaching the 3.3×10^7 kg ash was then calculated. These results, along with an analysis of the ash used in the experiment, are presented in Tables B-2 and B-3. The effect of gasification temperature on leachability was also examined; leachability appeared to decrease with increasing temperature from 1273 to 1573°K (1 hour reaction time), then became very stable above 1513°K when fusion occurred.

Sorption properties of porous media through which the pollutants are transported were then studied. Porosities and distribution coefficients (K_d) for water-soluble tar components (principally phenols), Ca^{+2}, Al^{+3} and OH^- were measured for unheated subbituminous Roland Seam coal.

It was shown that no preferential absorption of any of the four major tar components by the coal was evidenced. Sorption isotherms (organics sorbed, mg/kg, *vs.* organics remaining, mg/ℓ) were then obtained for the total soluble organic component (Figure B-3). Although coal had 10 times less sorptive capacity than several activated carbons, the shapes of the sorptive isotherms *vs.* concentration were similar. The distribution coefficient was a strong function of the initial concentration of the organics. K_d increased from 2.0 to 50.0 as the initial

* *For the OH^- ion, "clean" is assumed to be pH <10.0.*

Table B-2. ANALYSIS OF ASH (AS CONSTITUENT OXIDE) FROM COAL TYPICAL OF HOE CREEK TEST SITE*

Component	Wt. Percent
Phosphorus pentoxide, P_2O_5	0.39
Silicate, SiO_2	35.38
Ferric oxide, Fe_2O_3	2.03
Alumina, Al_2O_3	19.80
Titania, TiO_2	1.23
Lime, CaO	18.37
Magnesia, MgO	4.56
Sulfur trioxide, SO_3	16.98
Potassium oxide, K_2O	0.51
Sodium oxide, Na_2O	0.63
Undetermined	0.10
	100.00

* Wyodak Mine, Roland Seam subbituminous coal.
Source: L-8541

Table B-3. RESULTS OF LABORATORY INORGANIC LEACHING STUDIES

Ion	V_T(ℓ)	V_T'(ℓ)	t(y)
Ca^{+2}	0.140	4.6×10^5	26.0
Al^{+3}	0.037	1.2×10^5	7.0
OH^-	0.140*	4.6×10^5*	26.0

V_T = Volume of water necessary to leach "clean" 1 gram of ash

V_T' = Volume of water necessary to leach "clean" 3.3×10^5 kg of ash from the gasifier

t = Time required to leach the ash and clean with a flow rate of 175 m^3/y

* *Volume necessary to drop the concentration of OH^- by an order of magnitude.*

Source: L-8581

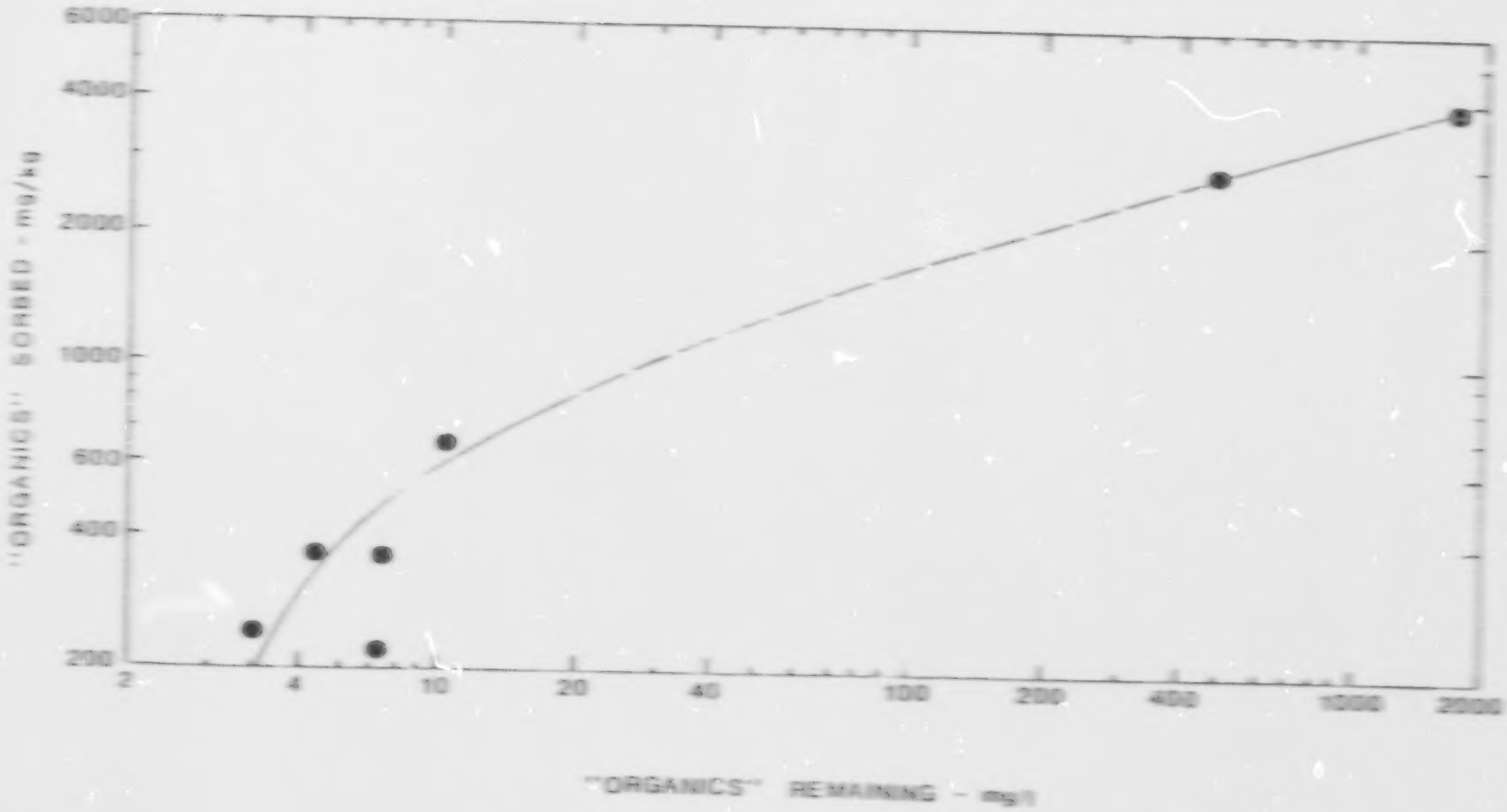


Figure B-3. SORPTION ISOTHERM FOR SOLUBLE ORGANIC COMPONENTS FROM COAL TAR ON SUBBITUMINOUS COAL
(Source: L-85KI)

concentration decreased from 2000 mg/l. Since this concentration is the maximum expected from any test, $K_d = 2.0$ was selected for use in the transport model.

The sorption isotherm for Ca^{+2} is shown in Figure B-4. The sorption of Ca^{+2} by subbituminous coal is significantly less than that for the organic component. K_d is approximately 1.0 and, over the range plotted, is independent of concentration. Sorption of Al^{+3}, on the other hand, is essentially infinite for sample concentrations ranging from 263 to 924 mg/l.

Since the OH^- radical reacts readily with phenolic functional groups in the coal, sorption could not be experimentally determined. Attempts to titrate the coal with NaOH were also unsuccessful. However, based on data reported in the literature, it was estimated that OH^- released from one gram of ash will be neutralized by approximately 1.5 grams of coal (L-8581).

Organic contaminants are assumed to originate from the char left in or near the gasification void. Water samples collected from the LLL "in-situ" simulation reactor contain between 1000 and 2000 ppm soluble organics (phenols) while water samples from laboratory pyrolysis experiments contain approximately 1000 ppm organics.

Results of Predictive Water Studies -

Some preliminary results of the predictive water quality studies have been reported. Based on laboratory and field measurements, the assumptions and inputs for the modeling of the Hoe Creek gasification test which are summarized in Table B-4 were selected and/or calculated.

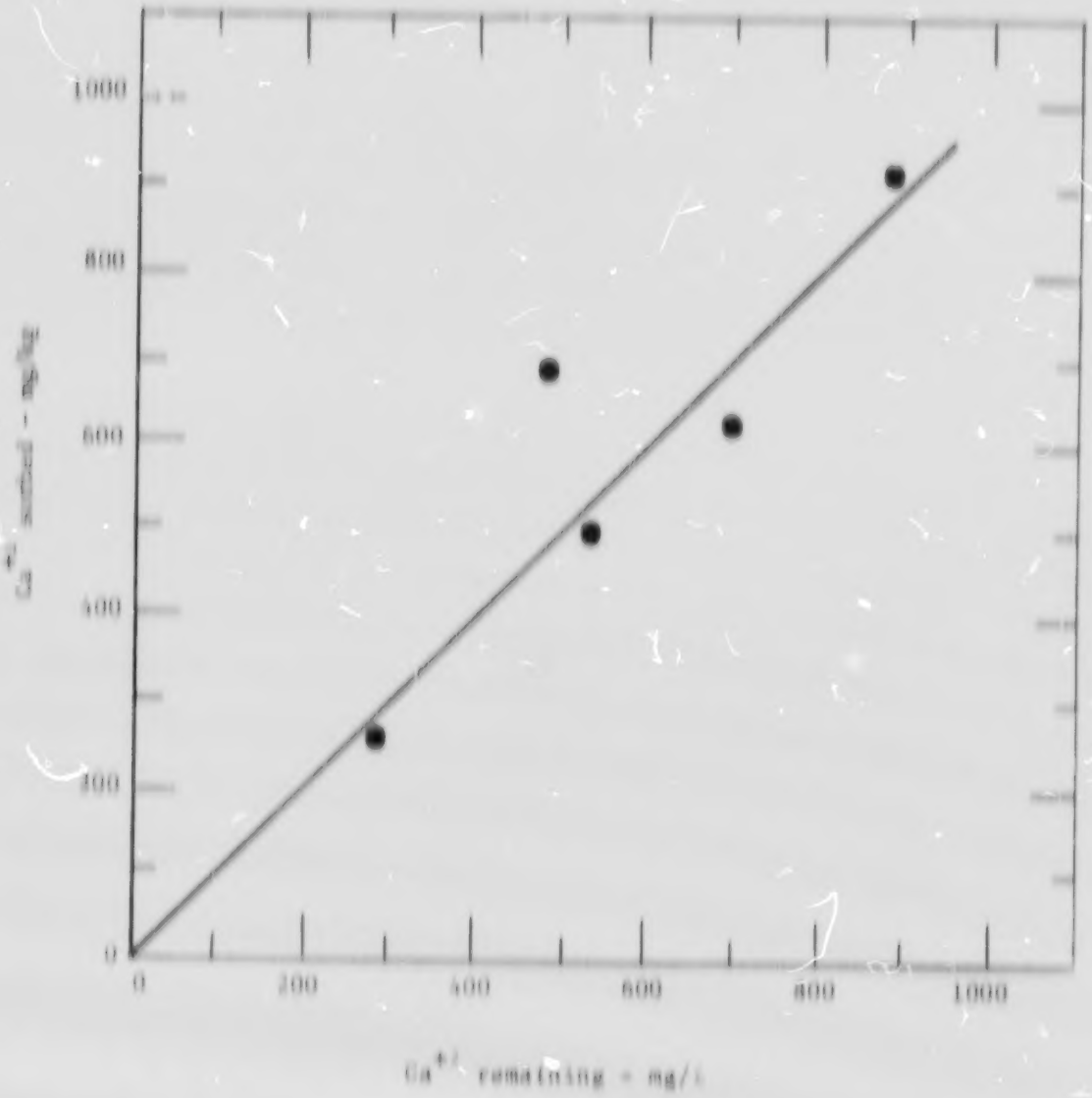


Figure B-4. SORPTION ISOTHERM FOR Ca^{+2} IONS ON SUBBITUMINOUS COAL (Source: L-8581)

Table B-4. SUMMARY OF INPUT PARAMETERS FOR WATER QUALITY MODEL CALCULATIONS

AQUIFER PROPERTIES

Flow velocity (V)	43.0 m/y
Total porosity (ϕ_T)	0.33
Interconnected (flow) porosity (ϕ_F)	0.05
Flow direction	easterly
Dispersion coefficients- $\frac{m^2}{y}$	$D = 1.5$, $D_t = 0.15$

SOURCE PROPERTIES

Material		Radius, R (m)	Initial concentration, C_o (conc. units)	Time to deplete source[a] (y) T_o	Rate of change of pollutant source conc. (C_o/T_o) (mg/ℓ y)
Ash	Ca^{+2}	5.2	400 mg/ℓ	26.0	15.4
	Al^{+3}	5.2	80 mg/ℓ	7.0	11.4
	OH^-	5.2	1.0×10^{-3} mol/ℓ[b]	26.0	3.8×10^{-5} mol/ℓ y
Organics		26.8	2000 mg/ℓ	2.0	0.0 (slug release)

[a]At flow rate of 43.0 m/y

[b]pH = 11.0

COAL SORPTIVE PROPERTIES

Material	Distribution Coefficient, K_d	Retardation factor R[a]
Ca^{+2}	1.0	14.4
Al^{+3}	∞	∞
OH^-	(reacts with coal)	-
Organics	2.0	27.8

[a]At 2000 mg/ℓ

Source: L-[58]

The aquifer properties include flow velocity and direction, porosities and dispersion coefficients. Although much lower local groundwater flow rates have been measured by LLL, the 43.0 m/y figure based on U.S.G.S. data was used as the model input. This will yield a maximum distance that the plume might travel in a year, assuming no major alterations in groundwater regime occur as a result of gasification.

Total porosity represents the total void space present in a material; however, since the pores are not all connected, not all the porosity is open to flow. In a typical subbituminous coal, the interconnected porosity (ϵ_F) is 0.05 compared to 0.33 (ϵ_T) for the total porosity. The quantity ($1 + \epsilon_T/\epsilon_F$) is the ratio of coal to water flowing through the coal. For the Hoe Creek site this ratio is 13.4. These parameters, along with the distribution coefficient for a specific component, are needed to describe the retardation effect on the movement of that pollutant caused by interaction with and passage through the coal.

The inorganic materials, as mentioned above, are assumed to be leached from the ash slowly over a period of time. Based on size of the source (i.e., estimated dimensions of the gasification zone), groundwater flow rate, and results of the laboratory leaching tests, the number of years required to deplete the source and the rate of change of the pollutant source concentration were calculated. Assuming the groundwater flow velocity and direction are not altered as a result of gasification, it was estimated that 26 years would be required to deplete the ash of Ca^{+2} and OH^{-}, while the Al^{+3} would be leached out in seven years.

The size of the area contaminated by tars during gasification will probably be determined by the water seal formed

by dewatering operations, the organics can be transmitted only as far as the formation water remaining in the coal seam. A more realistic as well as more optimistic approach, however, is based on the assumption that most of the gaseous tar components will condense within a few feet of the gasification zone. The less optimistic basis was used in the model, as was the assumption that the tar was deposited as a "slug" since no other time dependence could be postulated.

General conclusions regarding plume dispersion are as follows:

1. Because of the strong sorption effects of coal, the organic plume only moves approximately 1500 meters in 1000 years and its concentration is reduced from 2000 to 200 mg/l. The plume width is approximately 60 meters. These results are based on predictive models.

2. In addition, since K_d for organics increases as the concentration decreases, the remaining organics in solution will be essentially completely sorbed.

3. The Ca^{+2} plume concentration decreases in the direction of the gasifier as a result of the change in the source concentration with time. The plume is roughly 5 to 15 meters in width and 80 meters long. After 1000 years the modeled plume extended approximately 3000 meters downstream and the maximum concentration was 45 percent of that which originally prevailed at the source.

Air Quality Studies -

Studies are also being conducted to model the air pollution plume which is expected to result from the Hoe Creek gasification test. Air quality modeling parameters are presented for the Hoe Creek site in Table B-5. Table B-1 presented the expected composition of the product gas to be flared. The heating value is 5.3×10^5 J/Nm^3 (130 Btu/scf). Maximum expected product gas flow into the flare is 52 Nm^3/min (2000 scfm). The gas will be combusted in a 2:1 air/product ratio at about 1400°K. Source strength data for ignited and extinguished (i.e., malfunctioning flare operation) are given in Table B-6. Additional information on the model and anticipated results are available in the literature (L-5581). The general conclusion reached was that the Hoe Creek gasification test would not produce adverse air quality conditions, even under the worst operating conditions.

Kemmerer Field Test -

A small-scale, high-explosive fracturing test was conducted at this site. A 132-pound charge was detonated in a single hole 50 feet below the surface. Permeability improvements were then measured by drilling a series of core holes in the vicinity of the explosion. Test blocks of coal were also fractured with small charges to verify prediction methods. The results indicated that measured permeability and fracturing were in good agreement with preshot predictions for one- and two-dimensional stress-strain codes (L-8558).

Gillette Field Tests, Hoe Creek Site -

The Hoe Creek test site is located in the Powder River Basin approximately 20 miles south of Gillette, Wyoming (Figure

Table B-5. SUMMARY OF INPUT DATA USED FOR AIR QUALITY CALCULATIONS

Source	Flare Operating Condition	
	Ignited	Extinguished[1]
Effective source height (m)	10.0	10.0
Temperature (K)	1600	398
Gas flow rate (Nm^3/min)		
Fuel	52	52
Air	104	104
Heat flux (MJ/min)	275	8.5[2]
Atmospheric Conditions and Site Characteristics		
Wind speed (m/s)	4.0	
Stability category	Neutral (D)	
Mixing height (m)	250	
Topography	level	

[1] *The extinguished condition would result from a flare malfunction. Because it would lead to abnormally high ground-level concentrations, it is included in the calculation.*

[2] *Based on gas heat capacity of 8.0 cal/g-mole °C and an exit temperature of 60°C for the air-fuel mixture.*

Source: L-8581

Table B-6. SOURCE STRENGTHS FOR VARIOUS EFFLUENT GASES*

Flare Operation	Gas	Source Strength (m^3/s)
Ignited	CO_2	0.27
	SO_2	0.00095
Extinguished	CO_2	0.057
	CO	0.21
	H_2	0.16
	CH_4	0.019
	H_2S	0.00095

* *Calculated from the gas composition of Table B-1 and a flow rate of 52 Nm^3/min.*

Source: L-8581

B-5). It is proposed that the tests be conducted in the Felix No. 2 subbituminous coal seam which lies approximately 40 m deep and is about 7.6 m thick. The seam lies nearly horizontal with a tilt of less than 1°.

The water table at the site lies approximately 30 meters below the surface. Aquifers consist of the sand below 20 meters and the Felix No. 1 and No. 2 coal seams. Silt-clay aquitards lie both above and below the Felix No. 2 seam. Figure B-6 illustrates a stratigraphic view of the site and Table B-7 summarizes its hydraulic characteristics. The groundwater flow in the No. 2 seam is in an easterly (downward) direction. Although USGS data indicate a maximum velocity of 43.0 meters per year, LLL measurements yield much smaller local flow velocities (on the order of several meters per year). The horizontal hydraulic conductivity of the seam is very low; *i.e.*, about 0.15-0.27 m/day (0.5-0.9 ft/day) depending on the direction.

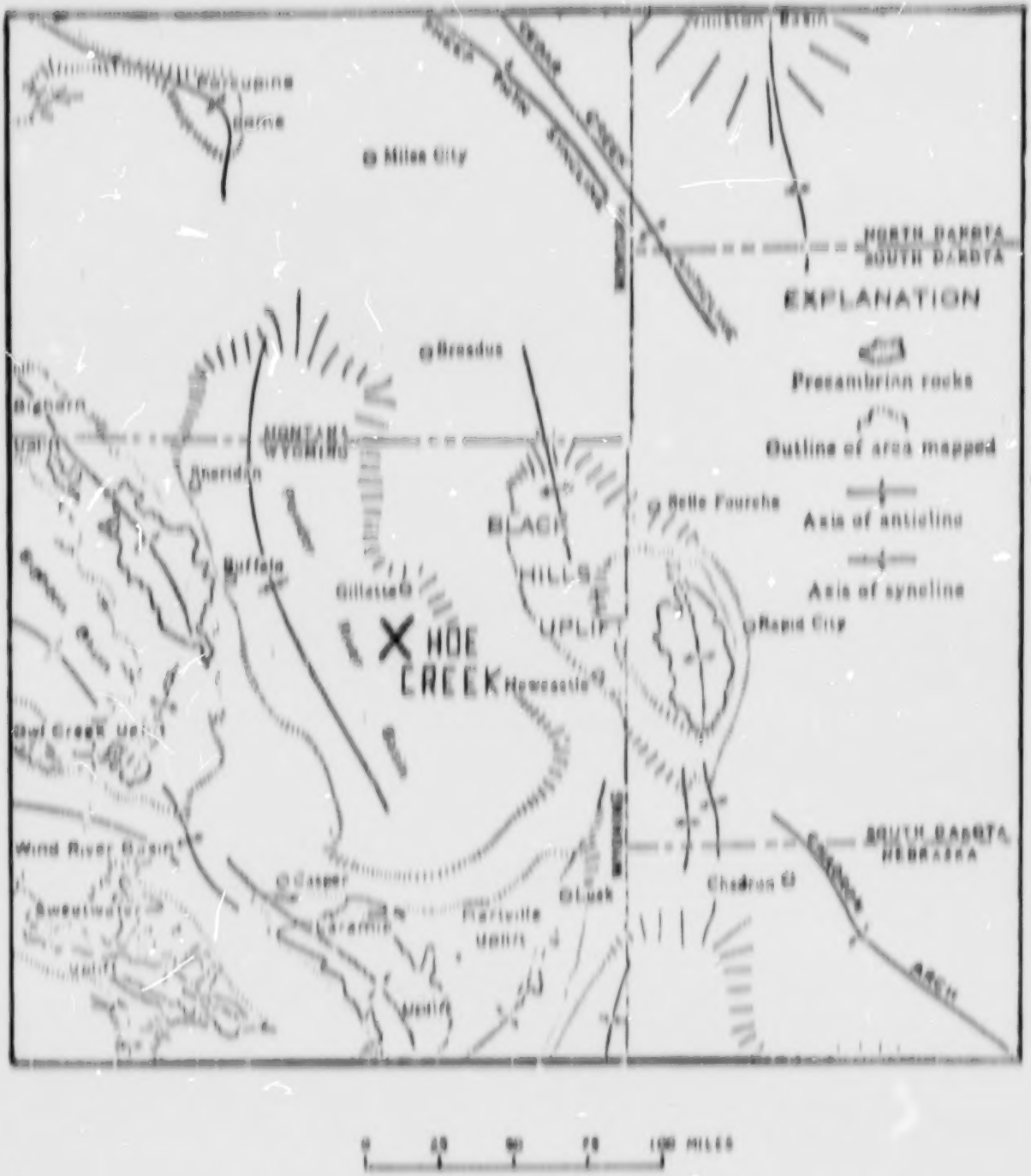


Figure B-5. LOCATION OF HOE CREEK TEST SITE
(Source: L-8582)

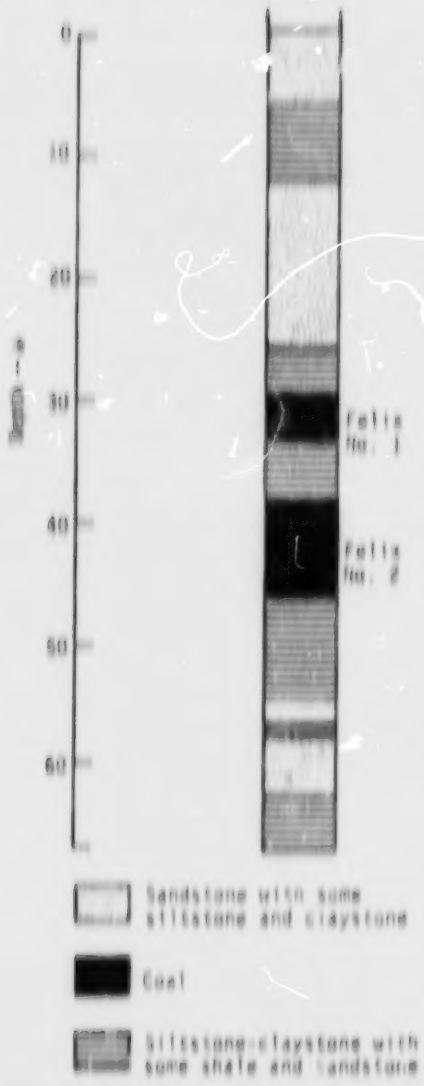


Figure B-6. STRATIGRAPHIC VIEW OF HOE CREEK SITE
(Source: L-8581)

Table 9-7. SUMMARY OF HYDRAULIC CHARACTERISTICS OF #2 COAL AND ASSOCIATED STRATA - MOE CREEK SITE

Rock Unit	Site	Horizontal hydraulic conductivity, m/day	Horizontal intrinsic permeability, m^2	Coefficient of storage	Vertical hydraulic conductivity m/day	Vertical intrinsic permeability m^2
Felix #1 Coal	I	0.304 to[a] 0.947	0.475 to[a] 1.42	2×10^{-2}	- No measurement made -	
Strata between Felix #1 and Felix #2	I	0.078	0.116	2.24×10^{-4}[b]	0.015[b]	0.022[b]
				5.02×10^{-4}[c]	0.002[c]	0.026[c]
	III	- No measurement made -		2.1×10^{-4}[b]	0.284[b]	0.430[b]
Felix #2 coal	I	0.272[d]	0.412[d]	1.28×10^{-3}	- No measurement made -	
		0.150[e]	0.177[e]			
	II	- No measurement made -			> Horizontal (not quantified)	
	III	0.325[f]	0.492[f]	1.6×10^{-2} to 4.15×10^{-3}	- No measurement made -	
		0.140[g]	0.212[g]			
Strata below Felix #2 coal	I	- No measurement made -			0.002[h]	0.0026[h]

[a] A range of values is given for two different single-well tests in the same well.
[b] Values are averages for the total thickness of strata between Felix #1 and Felix #2 coals.
[c] Values are averages for first 2.7 m of strata above top of Felix #2 coal.
[d] Value along axis of maximum hydraulic conductivity with trend of N 59°E.
[e] Value along axis of minimum hydraulic conductivity with trend of N 31°W.
[f] Measured along bearing of N 73°E.
[g] Measured along bearing of N 39°W.
[h] Refers to first 2.1 m of strata below bottom of Felix #2 coal.

Source: L-8582

A test pumping well drilled into the coal seam was able to sustain a pumping rate of only 3 gpm. Data from another source confirmed this low conductivity figure (the coal was reported to be capable of sustaining a pumping rate of only 4 gpm). The water level above the No. 2 seam is about 23 m (75 ft), and a hydrostatic pressure of 0.23 MPa (33 psi) was measured (L-8558, L-8581, L-8582).

The TDS levels in the three aquifers of interest decrease with increasing depth. The sand aquifer contains 2700 ppm TDS, while the upper and lower Felix seams contain approximately 2000 and 1000 ppm TDS, respectively (L-8544). Other chemical parameters for the three aquifers of interest are shown in Table 8-8 (L-8544).

The Hoe Creek test site was selected based on the following criteria required for relatively shallow test conditions (L-8558):

- Thick coal seam (15-50 feet)
- Shallow depth (<300 feet)
- Relatively flat coal bed
- Low permeability overburden
- No significant aquifer in either coal or overburden
- Suitable terrain for surface plant operations
- Closeness to utilities and all-weather roads
- Remoteness

Table B-8. CHEMICAL QUALITY OF GROUNDWATER FROM VARIOUS STRATA
HOE CREEK SITE 1

Chemical parameter[a]	Felix #1 coal	Strata between Felix #1 and #2	Felix #2 coal[b]
Sodium	60	80	75
Potassium	10	30	6.5
Total Hardness	750	1075	96
Iron	0.31	0.51	0.47
Bicarbonate	288	280	480
Sulfate	750	1100	174
Chloride	11	12.5	12.5
pH	7.3	7.5	7.8
Total dissolved solids	1882	2738	976
Conductivity	1900	2900	1000

[a]Concentrations in mg/ℓ, conductivities in μmho/cm.

[b]Average values for 2 samples.

Source: L-8582

The original test plan called for two tests. Hoe Creek Experiment No. 1, the preliminary experiment, took place on November 5, 1975. As illustrated in Figure B-7, this was a simple two-spot fracturing test in which two 750-pound explosive charges were fired simultaneously at the bottom of two holes 7.6 m (25 ft.) apart in the Felix No. 2 seam. If fracture evaluation had shown that good permeability had been achieved between these planned injection and production wells, an air gasification test would have been the next step. However, lower permeabilities than expected were achieved. Therefore, a second phase of Experiment No. 1 is now being planned (L-8558).

These plans call for drilling a new production well closer in. Gasification will then take place by a forward burn after dewatering. If plugging or low gas flow occurs, then a backward burn will be initiated to form a high permeability path followed by a forward gasification stage. The coal will be ignited at the top of the seam, with flow set up in a downward direction toward the highly permeable region and production well intake below.

Drilling preparations for the Hoe Creek Experiment No. 2, the 5-spot test, were already in progress at the time of the No. 1 Experiment. However, drilling was halted in December 1975. The objective of this test will be to fracture explosively and dewater a suitable zone, then over a 2-month period gasify approximately 3000 tons of coal in a 7.6 m (25 ft.) thick block about 15 m (50 ft.) on each side. Nearly 40 drill holes are planned in a circular area 30 m (100 ft.) in diameter. The general layout of these holes is shown in Figure B-8. The numbers of each type of well are itemized below:

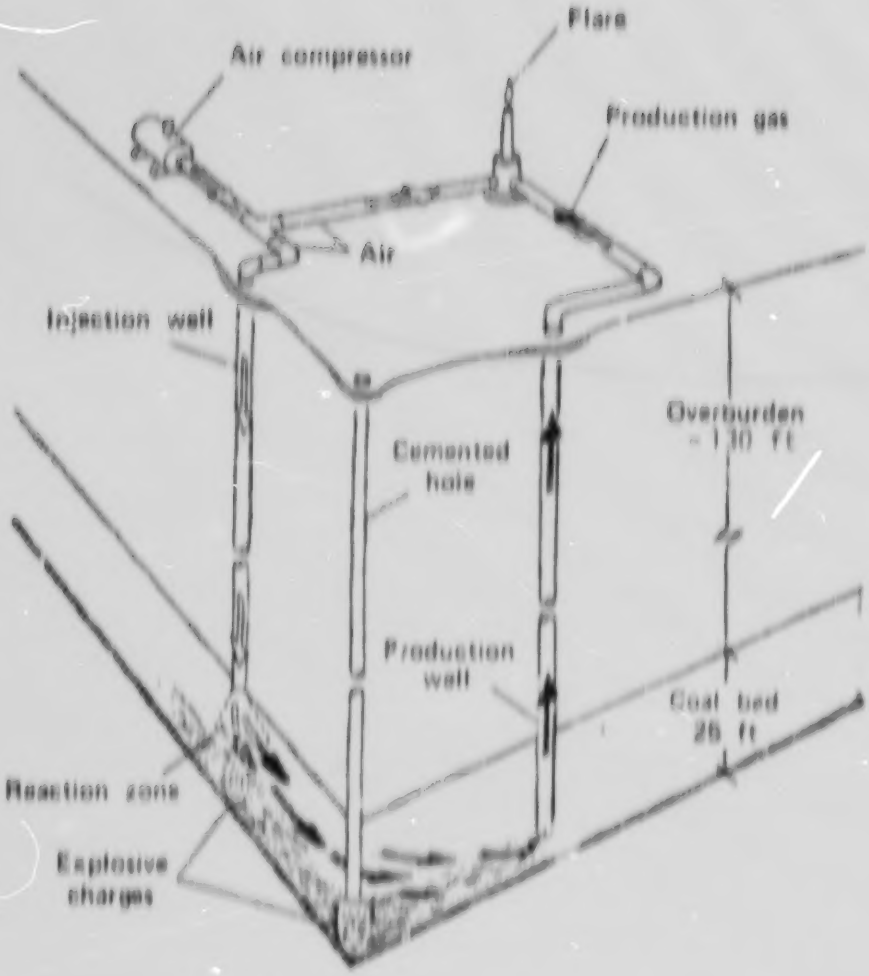


Figure B-7. SCHEMATIC DIAGRAM OF ROE CREEK EXPERIMENT NO. 1
(Source: L-8582)

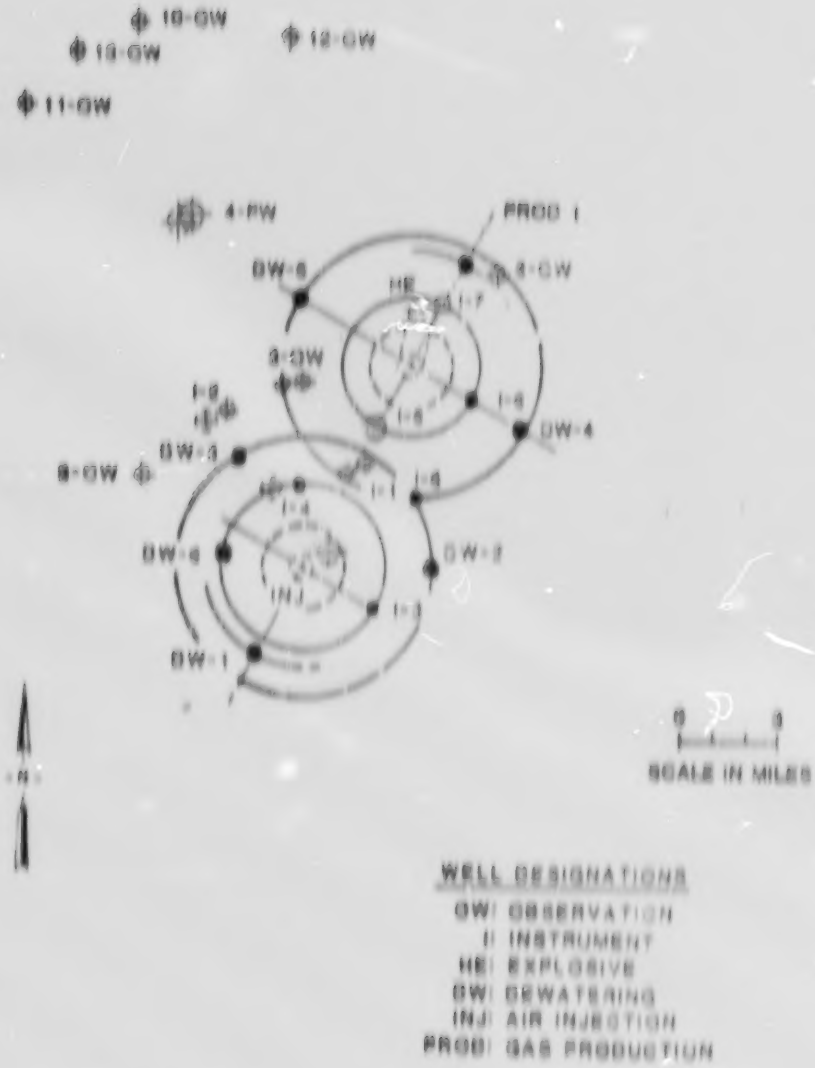


Figure 5-8. HOR CREEK NO. 2 EXPERIMENT
- FIVE-SPOT TEST -
(Source: L-8581)

5 - explosive fracturing

4 - dewatering

(1) - gas injection (center fracturing hole)

4 - production (10.6 m (35 ft.) from center)

13 - process instrumentation (thermocouples, gas pressure, liquid levels)

4 - subsidence monitoring (tiltmeters, extensometers, geophones)

7 - monitoring

Surface facilities will include a temporary gas processing plant with capability of supplying oxygen and steam and for sampling, metering and monitoring injection gases and product gases prior to flaring. Gaseous and liquid effluents will also be monitored. Additional plans call for material balance calculations to be attempted using an argon tracer technique (L-8544).

The planned dewatering operation will involve pumping water from the Felix No. 2 seam at about 20 gpm for about 10 days prior to gasification. This will involve removal of an estimated 1100 m^3 (300,000 gal) of water which could be used either as process water or for stock tanks. Dewatering will continue at a reduced rate (~10 gpm) during the 60-day gasification period, resulting in an additional 3800 m^3 (1,000,000 gal) of water requiring disposal. Monitoring will be continued throughout the dewatering operation.

APPENDIX C

MORGANTOWN ENERGY RESEARCH CENTER

In 1972 the Morgantown Energy Research Center (MERC) initiated a five-year, $10-million, ERDA-funded project to develop in-situ gasification technology for eastern U.S. coals. The project was based on the Longwall Generator Concept, designed to utilize the natural directional properties of the coal bed. This concept is perhaps the most versatile scheme for accommodating different modifications in directional flow control, controlled roof collapse, and hydraulic fracturing (L-2151).

The primary objective of this program is to study and identify the controlling mechanisms in underground coal gasification. It is hoped that through this study the following benefits will be gained:

- Improvement of the resource utilization efficiency
- Optimization of product gas heating value and composition
- Minimization of cost and environmental degradation

Scope of Work and Status

The MERC program consists of simultaneous theoretical, laboratory, and field projects. Each of these project phases and its purpose is outlined below. Presently, work in all three phases is continuing.

Theoretical Studies - Process simulation models of the coal bed in the UCG process totally disregard internal effects

(shrinking or swelling and phase changes) in the coal bed. To better understand the total process, studies are conducted at the micro, macro, and global levels with the hope of correlating the effects between these levels.

The three mechanisms believed to be the major contributing factors of the UCG process are:

1) The mass and energy transport processes

2) Reaction kinetics and catalysis

3) The stress-strain, structural effects

Laboratory Studies - The MERC UCG in-house laboratory effort is comprised of qualitative "effects" experiments; quantitative mechanical, thermal, and physical property determinations; and process simulation experiments.

Qualitative effects experiments are conducted on different type coals under various conditions to delineate the actual physics of the UCG process so that it can be realistically modeled. Simple oven tests where solid blocks of coal are heated at prescribed rates and temperatures clearly demonstrate relative reactivity, swelling or shrinking characteristics, phase changes, and preferred directional thermal fracturing.

Mechanical properties at elevated temperatures have not been sufficiently evaluated for UCG computations. Since these data will be necessary to realistically model the structural aspects of UCG, test facilities have been developed to obtain such data.

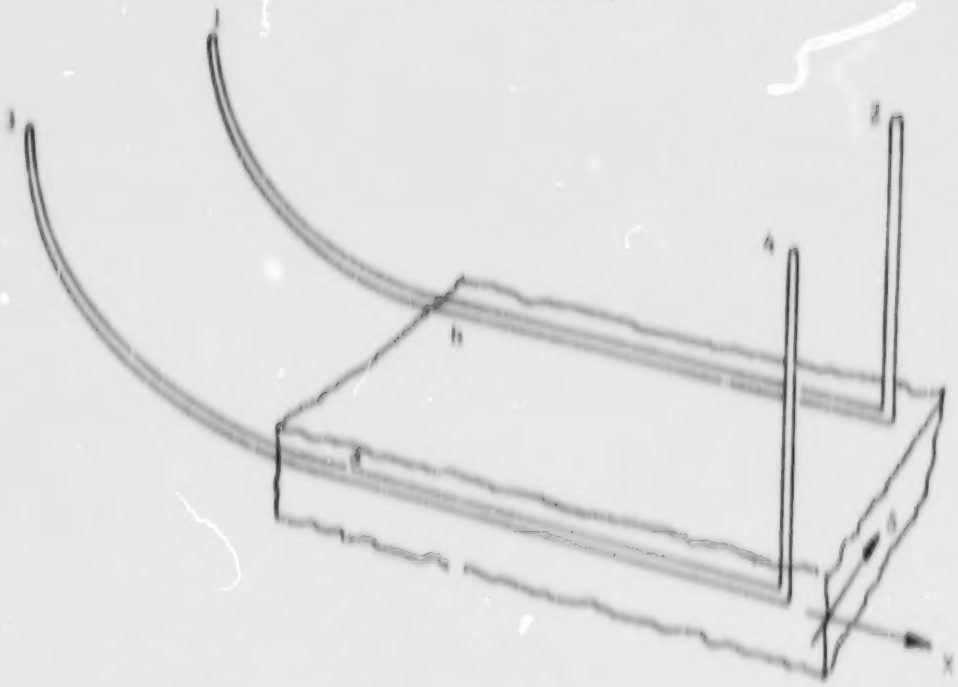
Field Project - The field work is being pursued in cooperation with Consolidation Coal Company and Continental Oil Company. This work is designed to demonstrate the feasibility of new directional drilling technology, which compliments the use of the Longwall Generator Concept. Figure C-1 illustrates the application of this concept to a power generation facility.

Use of directionally drilled holes can reduce surface degradation and environmental impact equal to or less than conventional oil and gas well drilling patterns. Vertical well UCG schemes require that patterns be drilled on less than 30-m (100-ft) square network spacing; this not only destroys the surface environment but also is not feasible in much of the eastern U.S. terrain overlying major coal deposits.

The field work will also be useful for determining the best reservoir preparation for gasification. One such preparation sequence is outlined in Figure C-2. Since there are several options for preburn bed characterization and gasification with two parallel, directionally drilled holes, each with a vertical hole intersecting its blind end, it is important to develop the best scheme for a particular coal.

The MERC underground coal gasification site is located in Wetzel County, West Virginia, near the small community of Pricetown. At this location the Pittsburgh coal is nominally 1.8 m (6 ft) thick and 1.5 m (5 ft) below the surface. The hydrogeology of the site has been characterized and the results have been reported (L-8395). To date drilling operations have been carried out on the first well. Problems have been encountered in achieving intersection of the directionally drilled and vertical holes.

(1/2 UNIT SHOWN)



I. <u>BED PREPARATION</u>

A. Pump water out of 4
B. Produce CH_4 out of 4
" " " " 3 and 4 (Low P.P.)
C. Pump water out of 2
D. Produce CH_4 out of 2
" " " " 1 and 2
" " " " 1 and 2, and 3 and 4
E. Inject air in 1 or 2 until O_2 increases and CH_4 decreases in 3 and 4
F. Inject Air in 1 or 2 until H_2O content decreases in 3 and 4
G. Miscellaneous pressure interference and other tests between Step A and G

II. <u>WELLBORE IGNITION</u>

A. Decrease air rate in 1 and 2 to preset value
B. Vent 3 while heating 4
C. Inject in 3 and reverse burn from 4 to 4

III. <u>BLOCK REVERSE BURN</u>

A. When ignition reaches 4, change mode
B. Inject in 1 and 2 and produce gases out of 3 and 4

Figure C-1. A LONGWALL GENERATOR DEVELOPMENT SCHEME

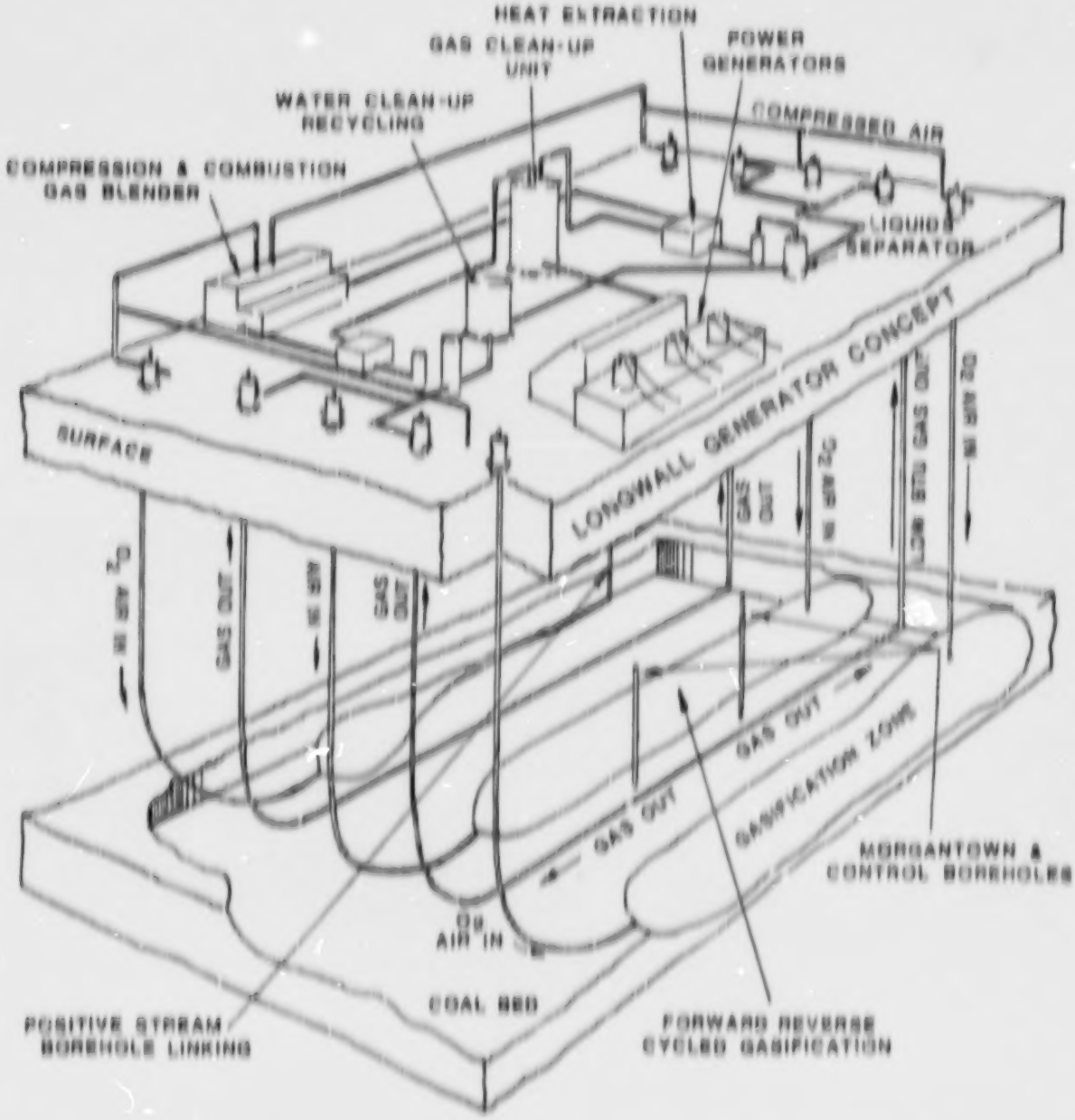


Figure C-2. LONGWALL GENERATOR CONCEPT
(APPLICATION TO POWER GENERATION FACILITY)
(Source: L-2151)

APPENDIX D

TUSI IN-SITU LIGNITE GASIFICATION PROJECT

In March of 1975 an agreement was signed between the Texas Utilities Services, Inc. (TUSI), and V/O Licensintorg of Moscow whereby TUSI was granted access to Russian in-situ gasification technology. This 2-million dollar agreement also gave TUSI exclusive licensing authority in the U. S. This is in conjunction with Williams Brothers Process Services, Inc., of Tulsa, Oklahoma. The Soviet Union will also receive modest royalties for any gas produced by their technology (L-1075, L-1436).

TUSI members involved in this project include Dallas Power and Light Co., Texas Electric Service Co., and Texas Power and Light Co.

The Russian technology, which dates back to the 1930's, has been applied in the USSR to a wide range of coals. Two UCG plants are currently in operation. One of these supplies fuel for a 30-MW power plant. The reported heating value of the gas generated is in the 3.5-4.1 x 10^6 J/Nm^3 (85-100 Btu/scf) range (L-1075, private communication).

The objectives of the initial test program are to determine the heating value and quantity of gas produced, the economics of the process and the existence and extent of adverse environmental effects associated with the technology. Its applicability to deep (>45 m (150 ft)) East Texas lignite deposits for electric power generation is the overall objective. Drilling and other site preparation work was initiated in March of 1975 and the first burn took place in August and September 1976, at the test site near the Big Brown Station near Fairfield. It is anticipated that a few months of operation will be sufficient to

demonstrate whether or not the technology is feasible for this application. A pilot-scale operation is also under consideration (L-1075, plus TWQB information; L-9166).

The major emphasis of the environmental studies is on groundwater contamination. Since the tests conducted or planned to date are of short duration and of limited intensity, no subsidence effects are anticipated. Deterioration of air quality is also receiving little attention at this time. The Russians claim that no adverse environmental effects have resulted in the USSR and in conjunction with this, a TUSI official reported that he observed "no visible evidence" of environmental problems at the USSR site he visited. A potential problem condition at the Texas site, however, may exist due to the presence of aquifers in the strata (L-1075).

Process Description

The technology to be investigated is based on a percolation method using air injection and producing wells. Permeability is achieved by means of high-pressure air or hydraulic fracturing techniques. Figure D-1 represents the process flow diagram for the test site. The basic features of the process are:

- Drilling and fracturing
- Ignition
- Linkage
- Gasification
- Product treatment/utilization
- Water treatment/disposal
- Dewatering

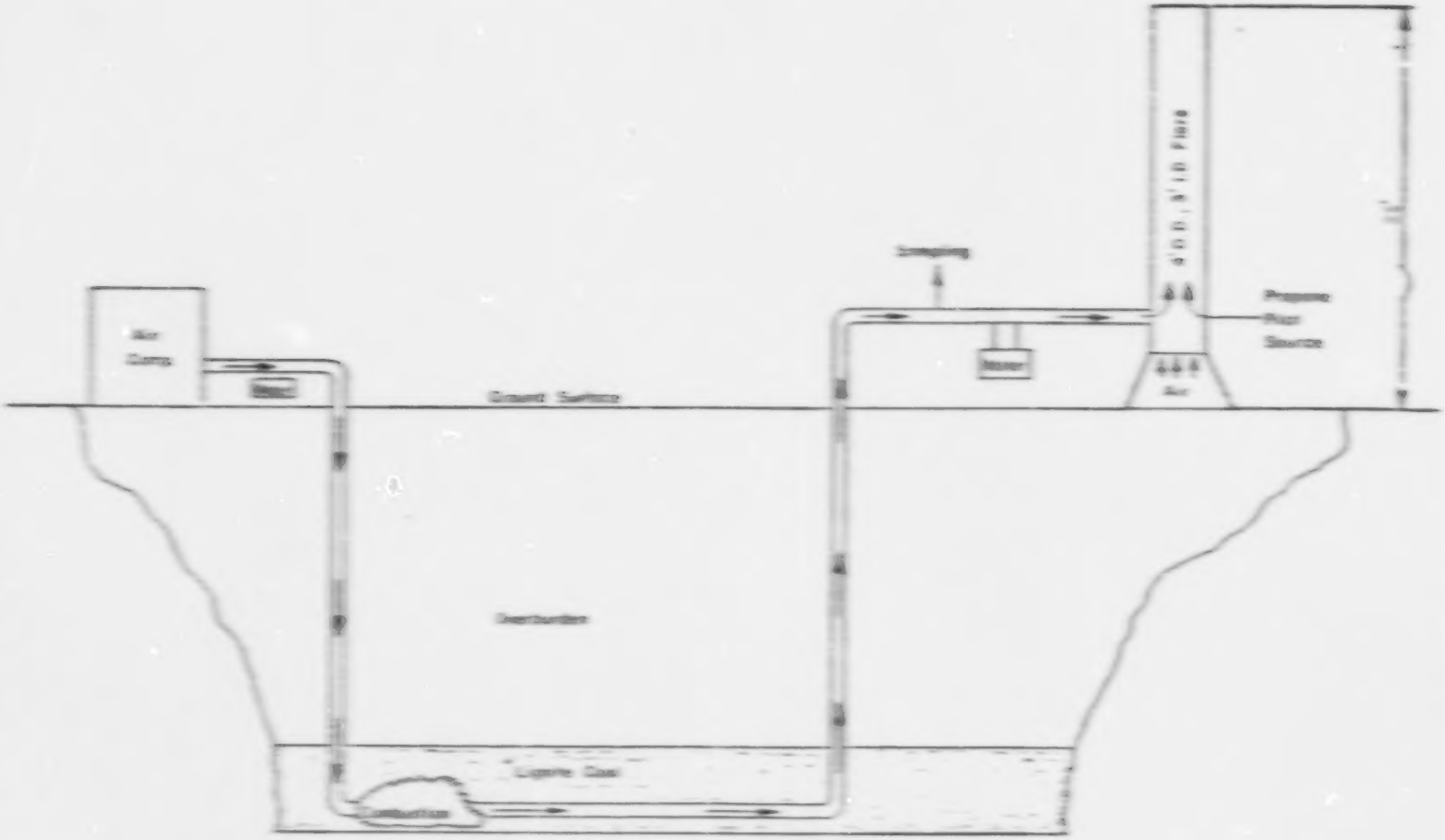


Figure D-1. PROCESS FLOW DIAGRAM FOR IN-SITU GASIFICATION TECHNOLOGICAL TEST SITE
(Source: L-9165)

A detailed description of the process to be tested at Big Brown is not readily available although it is probable that descriptive information given in a recently published overview of Russian technology can be applied here (L-8618).

After site selection and preparation, the test wells are drilled. Air injection is then carried out to determine the actual direction and separation of these wells. Once these are established, monitoring wells are drilled and fitted with appropriate instrumentation. Ignition is accomplished by first injecting compressed air to dewater the lignite at the bottom of the injection well. The temperature of the lignite is then raised by simultaneous injection of air and a burning fuel. Once ignition is established, linkage between the two injection wells is accomplished via a technique called "fire filtration linkage" and later between the two producing wells (L-9165). The water supply for the gasification reaction is the groundwater present in the coal seam. Site-specific details of the Big Brown test are provided in the next section, Project Scope and Status - Field Test.

Project Status and Scope

Since signing of the agreement in March of 1975, activities have been carried out in the following areas:

- Site characterization and preparation
- First gasification test
- Water quality studies

Specific approaches and results to date in each of these areas are described in the following text.

Site Characterization - The site selected for the gasification test is located near the Big Brown Steam Plant at Fairfield, Texas, in Freestone County. The lignite seam to be gasified is situated 67 m (220 ft) deep under hydraulic head of 49 m (160 ft). Aquifers are located in five different strata at the test site; these include units 3, 9 (upper lignite seam), 11, 13 (lignite seam to be gasified) and 15, as indicated in the stratigraphic view of the gasification site (Figure D-2). Geologic descriptions of all the units shown are available in the permit application to the Texas Water Quality Board (L-9165). Existent water quality data are presented in a later subsection of this project description (L-9166).

Site preparation activities consisted of drilling three test wells, ten water quality monitoring wells, and three temperature wells in the area. Their approximate locations are indicated on Figure D-3. Well numbers identify the unit into which the well is drilled (refer also to Figure D-2). The water quality wells and the respective units being monitored are as follows (L-9166):

Well No.	Unit
TTS 3-1	3
TTS 9-1	9
TTS 11-1	11
TTS 11-2	11
TTS 13-1	13
TTS 13-2	13
TTS 13-3	13
TTS 13-4	13
TTS 15-1	15
TTS 15-2	15

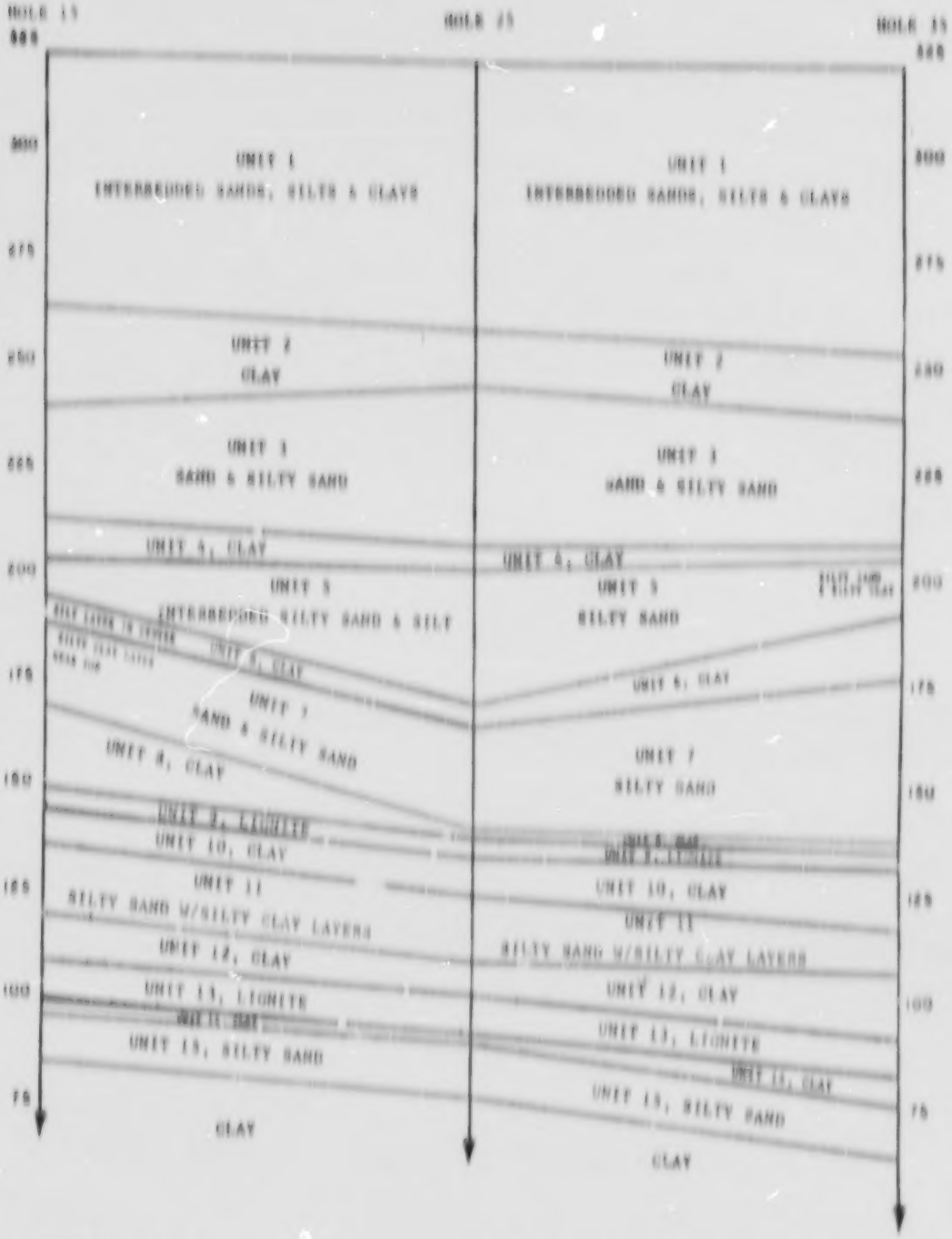
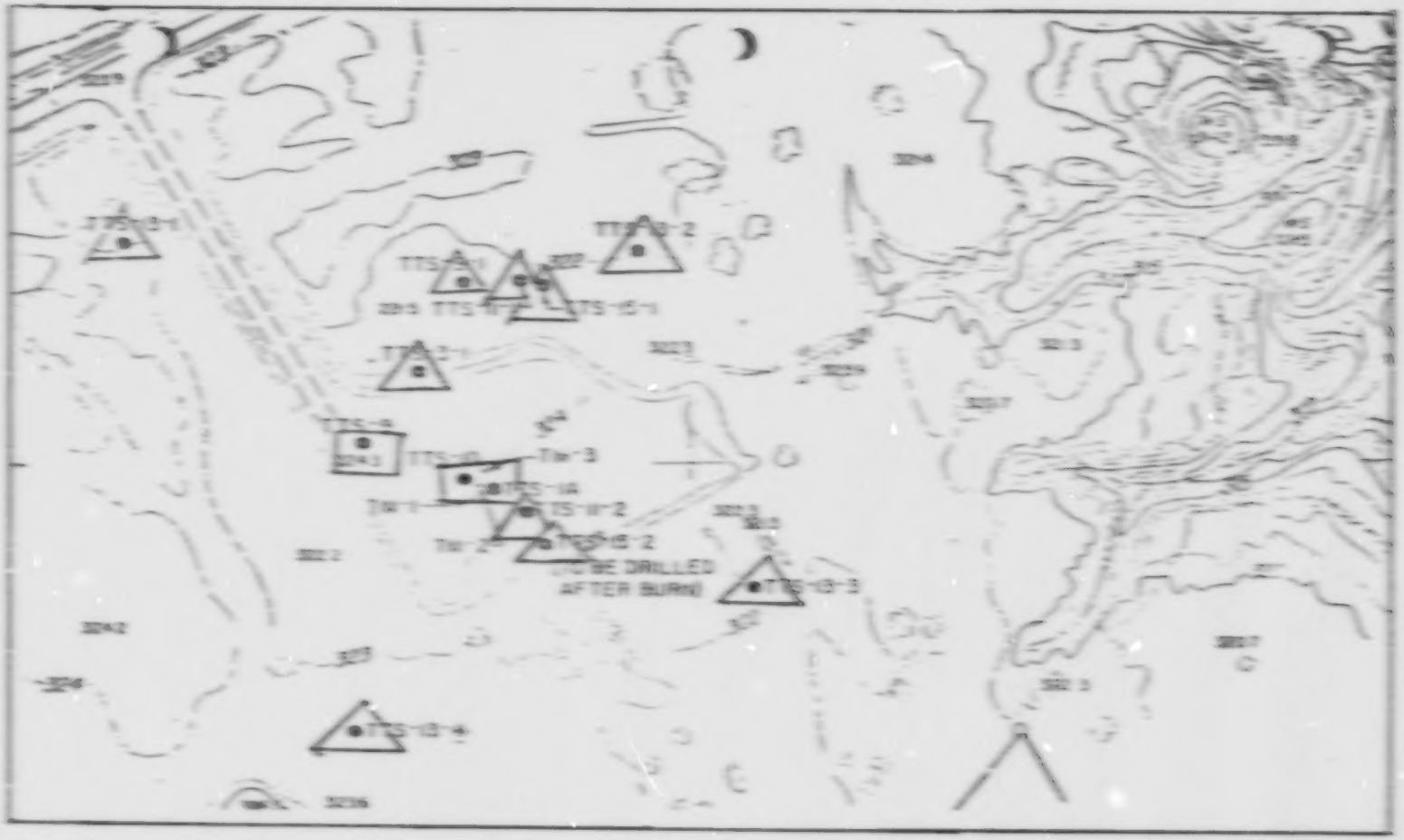


Figure D-2. TUSI IN-SITU LIGNITE GASIFICATION PROJECT STRATIGRAPHIC CROSS SECTION OF TEST AREA (Source: L-9166)



Scale: 1" = 100'

Figure D-3. MONITOR WELL LOCATIONS AT TECHNOLOGICAL TEST DRILLING SITE
(Source: L-9166)

Details regarding construction of temperature monitoring wells (TM-1, TM-2, TM-3) are given in the permit file. There are three test wells specified, all of which are approximately 67 m (220 ft) deep and within 30 m (100 ft) of each other. The ignition well is identified as TTS-10 and wells TTS-9 and TTS-1A serve as injection wells. Well TTS-9 will be used only for air injection, while Nos. 10 and 1A will also serve as gas draw-off wells (L-9165, L-9166).

Field Test - The in-situ gasification test was initiated on August 15 (air injection) and ignited on the 17th. The operation was shut down after 28 days because of inferior product gas quality which resulted from operation at a much reduced operating pressure required to control in-situ water quality. The product gas from this test was flared after monitoring; no data were available in the public domain, however, regarding gas quality. The test can best be described by a tabulated chronology of events compiled from several documents in the public files.

6/22 Public hearing held

7/29 TWQB approved permit

8/15 Air injected into the formation to "dry-out" the production area

8/17 Formation ignited at base of TTS-1A by simultaneous injection of air and a burning fuel with air flow from TTS-10 to TTS-1A. Air flow reversed after 7 hours.

8/19 Completed "Link," TTS 10 & TTS 1A

9/01 Completed "Link," TTS 10 & TTS 9

9/03 An upward trend was recognized in conductivity in monitoring wells TTS 11-2, TTS 13-2 and TTS 13-4, along with a reduction in pH in well TTS 11-2. Operating pressure was reduced from 0.58 MPa (69 psig) (formation hydrostatic pressure) to 0.43 MPa (48 psig) and notified TWQB.

9/04 Further increase in conductivity and decrease in pH was noted in well TTS 11-2. The well was pumped to clear the casing and another sample taken which was similar to that recorded on the 3rd. Analysis of a sample taken later in the day indicated a further reduction in conductivity.

9/05 The reduced pressure appeared to cause an improvement in conductivity levels so the pressure was raised to 0.52 MPa (60 psig) (0.16 MPa or 9 psig below hydrostatic) in an attempt to improve produced gas quality without affecting the conductivity of the water.

9/06 & 9/07 Conductivity reading increased significantly in wells 13-2 and 13-4. Pressure was returned to 0.43 MPa (48 psig) to reverse the upswing, resulting in minor improvement.

9/08 -10 A minor improvement appeared to occur during these days.

9/11 The operating psig was progressively reduced to
-13 0.29 MPa (28 psig) until the gas quality was too inferior to continue. At this time injection of air was discontinued. It is anticipated that water will now return to the gasified area and extinguish the flame. This will terminate the test phase of the operation and begin the restoration phase.

10/07 At this time the water table had almost returned to normal levels, but the temperature near the burn area remained high, 93-149°C (200-300°F).

Plans for closure specify full-length cementing of the wells to be abandoned.

Water Quality Monitoring - As described above, ten water monitoring wells were drilled at the test site. Baseline data for criteria parameters for nine of these wells as determined from analysis of the samples are presented in Table D-1. Available measured levels for other parameters in geological units of interest are presented in Table D-2. Analyses are also being conducted periodically for the following additional species:

NO_3 as N	Total Fe
H_2S	As
CN^-	Ba
CH_4	B
SCN^-	Cd
TOC	Ag

Frequency of sampling during the gasification period is specified in Table D-3. For at least six weeks following the burn, weekly samples will be taken, to be followed by monthly sampling until restoration commences.

Table D-1. BASELINE WATER QUALITY STANDARDS FOR TEXAS LIGNITE GASIFICATION PROJECT

Well	Temperature (°C)	pH	Cond. (μmhos)	NH_3-N (ppm)	SO_4 (ppm)
TTS 3-1	23.3	8.1	530.0	.19	58.3
9-1	22.0	8.7	361.4	.19	.6
11-1	22.0	9.17	386.7	.20	11.3
11-2	22.1	8.31	394.7	.20	10.6
13-1	22.2	8.50	459.0	.26	16.1
13-2	22.3	9.35	507.5	.35	11.5
13-3	22.1	9.58	557.7	.35	25.3
13-4	22.2	8.75	479.5	.36	19.9
15-1	22.3	9.63	533.3	.40	57.0

Source: L-9166

Table D-2. ADDITIONAL BASELINE QUALITY PARAMETERS OF WATER IN GEOLOGIC UNITS

Parameter	Concentrations - ppm					
	*C	Unit 3	Unit 9	Unit 11	Unit 13 (Production)	Unit 15
Chloride	*250 #	216	96	30	84	30
Chromium (Hex)	* .01 #	-	-	<.05	<.05	-
Copper	* 1.0	2.1 #	<.1	<.1	.05	<.1
Lead	* .05	-	-	<.1	<.1	<.02
Manganese	* .05	17.4 #	.6	<.1	<.01	<.05
Mercury	* .002	-	-	<.0001	<.0001	.0006
Selenium	.01	-	-	.005	* .022	.025
Sulfate	*250	47	72	18	37	40
TDS	500 #	940 #	590 #	275	*1130	350
Zinc	* 5	-	-	.90	.94	.35
Bicarbonate	-	81	254	-	-	130
Carbonate	-	-	-	20	34	40
Calcium	-	173	77	14	8	10
Magnesium	-	26	23	9	5	2
Sodium	-	72	50	64	84	80
pH	* 6-9	7.6	7.4	8.3	6.7	8.6
Phenols	.001	-	-	.30 #	* .36	.06

* Expected restoration value for production zone aquifer.

\# Expected restoration value for upper and lower aquifers.

Source: I-40m

Table B-3. SAMPLING FREQUENCY FOR GASIFICATION PERIOD

	Temp.	pH	Cond.	SO_4	NH_3-N	Water Level
Unit 13 Wells (4) (Temp. only for TN1, 2 & 3	3	3	3	1	1	3
Unit 15 Wells (2)	1	1	1	1	1	1
Unit 11 Wells (2)	1	1	1	1	1	1
Unit 9 Well (1)	1	1	1	1	1	1
Unit 3 Well (1)	1	1	1	1	1	1

Source: L-9166

Procedures were also specified in the permit in case of an excursion. An excursion was defined by any of the following occurrences:

- Increase in conductivity by 200 micromhos
- Increase in NH_3-N by 5 ppm
- Increase in $SO_4^{=}$ by 100 ppm
- Significant variation in pH

In the event of an excursion possible actions to be taken include (L-9166):

- Drilling of additional holes in the direction of the groundwater movement at 15- to 30-m (50- to 100-ft) intervals

- Adjustment of operating conditions

- Pumping of monitoring wells to intercept the contaminated groundwater

- Termination of test

In the case of dewatering, three possible disposal methods were cited in the permit (L-9166). These included discharge into either the retention pond at the coal storage area or the ash pond at Big Brown or storage on site and subsequent utilization for dust suppression on haul roads. The selection of which of all the above possible actions to be taken was to be based on the nature and level of the contaminants.

Recently, additional arrangements have been made to conduct GC-MS analyses of four specified water samples (Wells TTS 10, 13-11, 13-2 and 11-2). Results of these analyses to identify organic components are not yet available (L-9166)

Results of the water monitoring program to date are available in the Texas Water Quality Board files. In summary, the following observations can be made:

1. Temperature and NH_4-nitrogen were unaffected in all wells.

2. Decreases in pH were measured in the four wells located in Unit 13 (the lignite seam

being gasified) and in one of the wells in the overlying aquifer (Unit 11). These decreases were first noted as soon as one day after air injection was initiated in one case (No. TTS 13-2). After a period of from 3 to 31 days the pH levels had increased to apparently steady but below-normal levels.

3. Conductivity increases were observed within a few days following pH decreases in all of these cases.

4. Some slow tailing-off of sulfate levels in the affected monitoring wells was also observed.

Water quality analyses of other than criteria pollutants mentioned above were not yet available for the gasification and follow-up period.

Some general conclusions may be drawn although they may be premature. It has been suggested that the observed decrease in pH may be due to CO_2 in the water from the injection of air into the seam. In any case, pH serves as a better indicator of excursion than conductivity since it drops sooner than observed rises in conductivity. The apparent excursion into Unit 11 may mean that in a full-scale process, overlying aquifers may present a more serious problem than production zone aquifers since upper aquifers generally are of greater quality and quantity. However, the lack of a continuous data base due to problems in sampling of this well causes due concern for validity of conclusions drawn from these data.

APPENDIX E

UNIVERSITY OF ALABAMA - FEASIBILITY STUDY OF IN-SITU COAL GASIFICATION IN THE WARRIOR COAL FIELD

A two-year technical feasibility study of in-situ gasification of thin bituminous coal seams is currently underway at the University of Alabama. The program was initiated in August of 1975 under an NSF grant. Additional funding is provided by the Alabama Power Company, the Mineral Resources of Alabama and the University of Alabama.

The approach developed to achieve the objective of this program involves seven basic tasks:

- Site selection
- Site-specific studies of geology and physical coal properties
- Determination of the air acceptance properties of the seam
- Development and operation of laboratory combustor
- Development of linking techniques that will allow high resource recovery along with a controllable gasification process
- Development of analysis techniques for multi-parameter investigations
- Establishing baseline environmental characteristics of the site

All information contained in this section of the report is based on the second semiannual project report (L-8617) published in October 1976.

Process Features

The process details of the University of Alabama's plans for in-situ gasification are not defined at this time. As stated in the previous section, their process is aimed at gasification of thin coal seams (<1 meter) of eastern bituminous coals. Fracturing techniques are still under investigation although vertical hydraulic fracturing is being emphasized. Follow-up linkage by reverse combustion appears the most feasible at this time with air gasification in the forward direction. Estimated product quality and flow sheets for this process were not available at this early stage.

Project Status and Results

The status and results after completing the first year of this two-year program are summarized below. Details are available in the semiannual report (L-8617).

Site Selection - This task has been completed. The gasification site is located two miles north of Adger, Alabama, in Southern Jefferson County. It is located above the Gwin Seam of the Warrior Coal Field, as illustrated in Figure E-1. The coal seam to be gasified meets the requirement of being less than 1 meter thick; at the test site the coal is 0.86 m (34 in) thick and lies under 79 m (260 ft) of overburden, although the depth varies considerably from 0-104 m (0-340 ft) throughout the general area. The overburden consists of sequences of dark gray siltstone, fine-grained sandstone and shales.

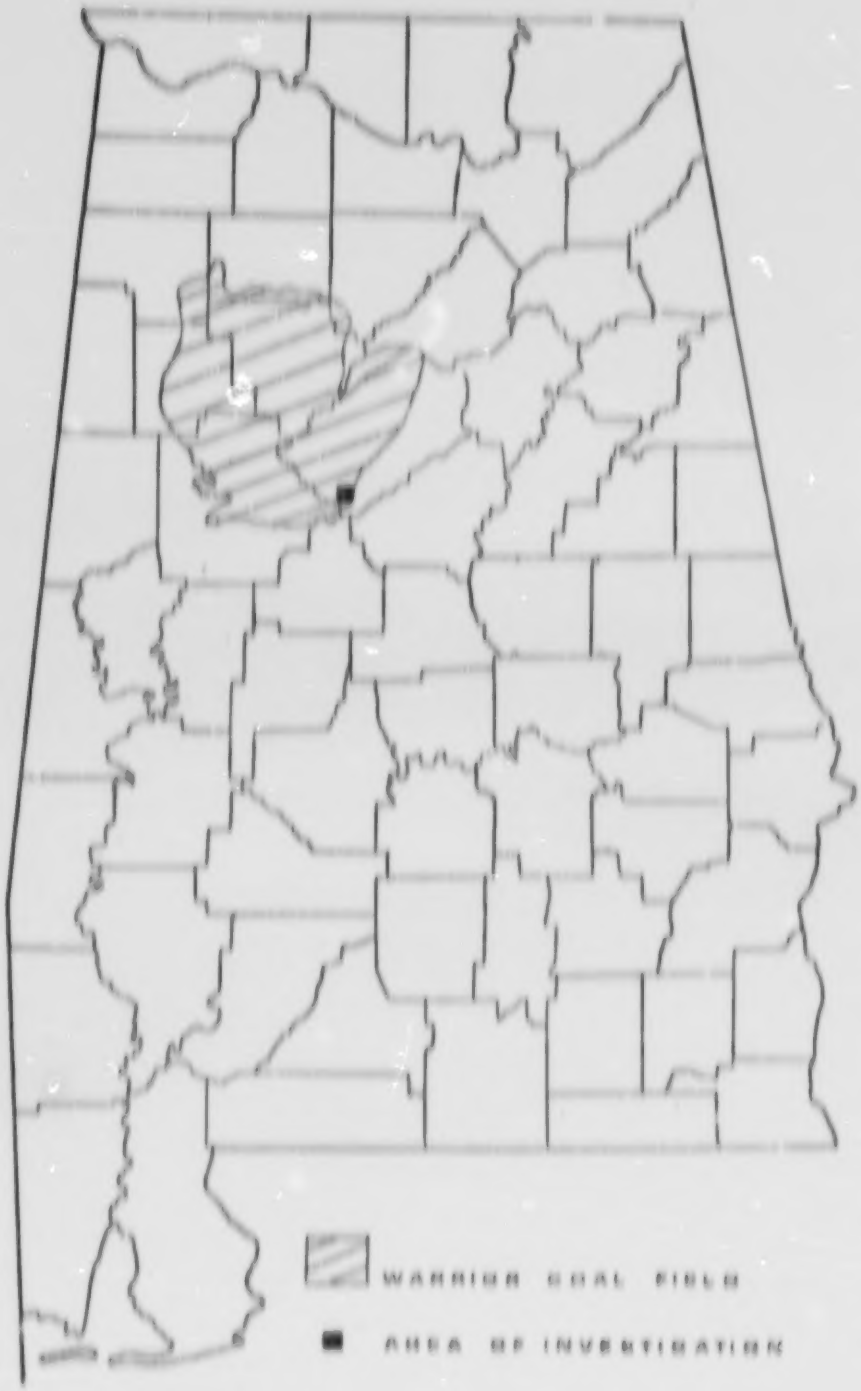


Figure E-1. LOCATION OF THE EXPERIMENTAL IN-SITU GASIFICATION STUDY AREA WITH RESPECT TO THE WARRIOR COAL FIELD IN ALABAMA (Source: L-8617)

Geological and Coal Properties Studies - Significant progress has been made in this second task area. During the geological studies the coal and overburden have been characterized for the general area as well as the specific test site. Figure E-2 presents the lithology of the experimental gasification site as determined by a core sample. The test area is located in the drainage area of Valley Creek, which flows into the Black Warrior River. It has also been determined that two or possibly three faults are present in the vicinity of the test site.

The following coal properties were compiled from available data for Alabama coals:

- Proximate analyses (moisture, volatile matter, fixed carbon, ash)
- Ultimate analyses (H, C, N, O, S)
- Heating value
- Free swelling index and other swelling properties
- Agglutinating value
- Plastic properties
- Other physical properties (breakage, friability, grindability, hardness, etc.)

Most coals in the Warrior coal field are characterized as high or medium volatile bituminous. The Gwin seam contains strongly

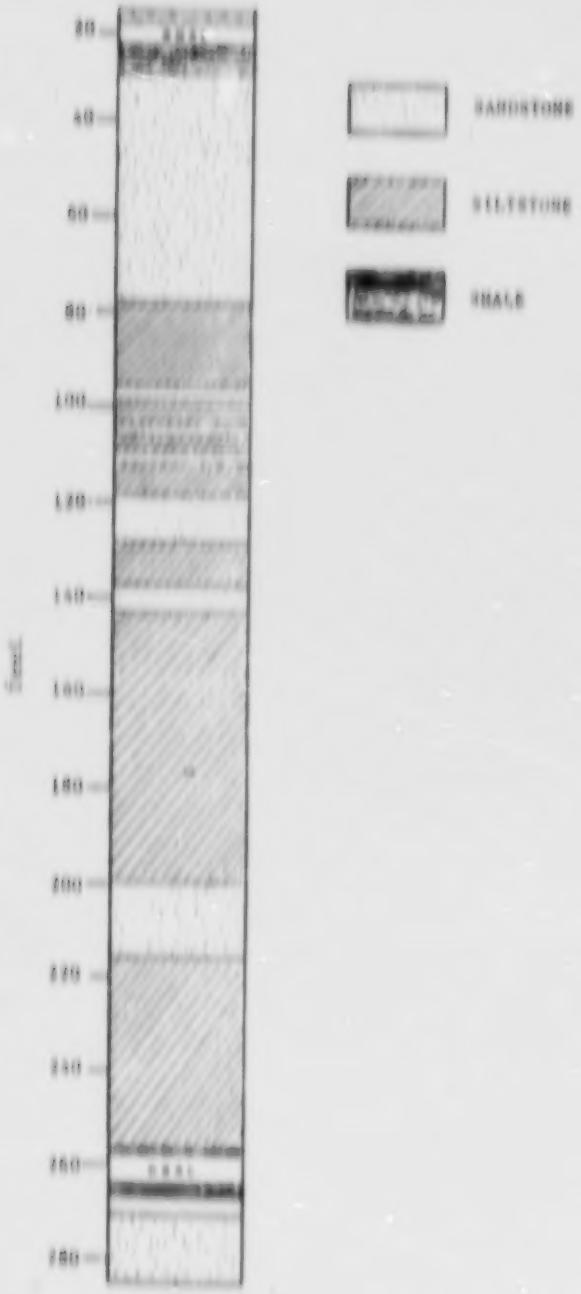


Figure E-2. LITHOLOGY PRESENT IN IN-SITU GASIFICATION CORE HOLE 1-A AT EXPERIMENTAL GASIFICATION SITE (Source: L-8617)

swelling coal of HVB rank. No published analyses were available. Two to three tons were sampled for use in the laboratory studies, but this coal was so friable (easily crumbled) that it could not be used in the combustor. Several coals from adjacent seams in the Warrior field were collected for these tests, which will be addressed in another section. The Utley (or Clements) seam, for example, which lies 70 m (230 ft) above the Gwin seam, is assumed to be similar to that in the gasification site.

Air Acceptance Properties of the Coal Seam - This part of the program is also in progress. Air acceptance is a measurement of the rate at which air, or another gas, can be forced into a coal seam, through a drilled and cased borehole, at a certain pressure. Two test holes have been drilled at the site and several more are planned. No results are available yet.

Laboratory Combustor Studies - A bench-scale combustor system was designed and constructed in order to provide data for correlation between product gas quality and input variables. The gas flow system is illustrated in Figure E-3 and details are available in the semiannual project report. To date some meaningful results have been obtained and this phase of the program is continuing.

The combustor tests were conducted using coal block samples having a single vertical crack up the middle in the direction of the air flow. This crack simulates a simple case of conditions resulting from hydraulic fracturing of the coal seam. Severe plugging problems occurred during trials of forward combustion due both to swelling close to the reaction zone and tar condensation further down the crack. This was not the case during reverse combustion runs; the reaction in this mode, however, does

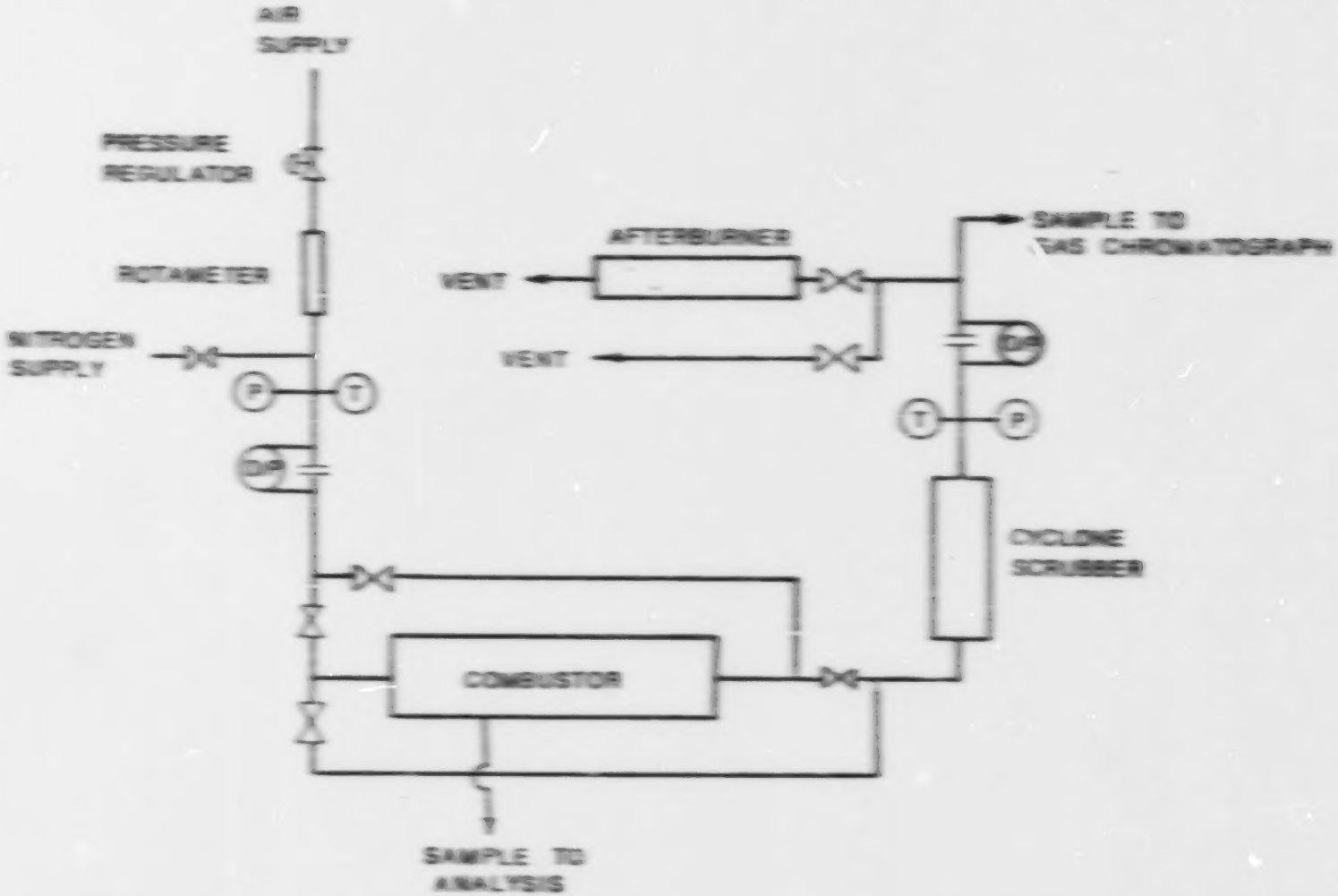


Figure E-1. GAS FLOW SYSTEM FOR LABORATORY COMBUSTOR
(UNIVERSITY OF ALABAMA)
(Source: L-8617)

not produce a satisfactory product gas. Therefore, further testing was carried out to study its feasibility as a linking mechanism following hydraulic fracturing. The following problems are under investigation:

- Required air flow to support combustion at the maximum rate without excessive blow-by

- Kinetics within the char region under the influence of air passing from the crack region to the outer edges of the combustion zone

- Heat transfer from the combustion zone into the unburned coal

Details of these studies are available in the literature (L-8517).

Development of Linking Techniques - This work is also in progress. Present plans call for initial fracturing by hydraulic fracturing techniques to be followed up by reverse combustion to complete the linkage. Some of the basis for this design was developed during the laboratory combustor tests.

A theory for predicting fracture direction for in-situ gasification processes is being developed as part of this phase of the program. Bureau of Mines and other field data are being used to aid in the development and verification of a hydraulic fracture model of coal that considers the directional permeability and directional tensile strength properties of coal. It has been shown that under certain conditions coal will fracture along its face cleat direction rather than perpendicular to the least principal stress as predicted by conventional fracture theory.

Also under consideration as a possible fracturing or linkage technique is the Bureau of Mines' (MERC) deviated drilling or laser drilling approach.

Development of Numerical Analysis Techniques - The objective of this support task is the development of numerical techniques to supplement the laboratory studies and to aid in predicting the results of planned field work. Topics currently under investigation include:

- Advance rate and lateral extent of combustion front during reverse burn

- Heat transfer associated with advance of the combustion front

- Fluid flow associated with advance of the combustion front

Groundwater Contamination Studies - This effort is aimed primarily at defining potential long-term contamination of groundwater by leaching of gasification residues rather than immediate or short-term effects due to gas leakage during the burn. Both organic and inorganic contaminants are being considered. The major portion of planned baseline monitoring is now completed and monitoring by the Geological Survey of Alabama is continuing. The research studies involve both laboratory and modeling activities. The approach and results to date in these different areas are described below.

The geology and hydrology of the experimental site have been characterized. The coal seam to be gasified lies below the dry-season water table. The presence of several faults in the

lower Pottsville formation contributes to increased groundwater flow in the area. The permeability of the formation and the pressure gradient were determined to be approximately 150 darcies and 9.5 meters of water/kilometer (50 feet/mile), respectively. Combined, the superficial water velocity is approximately 0.0015 cm/sec (1600 ft/year).

Laboratory leaching studies were conducted using coal similar to that in the Gwin seam pyrolysed under the following laboratory conditions.

- One hour to raise temperature of mass to 650°C
- Few minutes to raise temperature to 1200°C
- Reduced air flow to achieve partial combustion; reaction complete within a few minutes
- Sample cooled

Analyses of the coal and the carbonization residue are presented in Table E-1.

Leaching studies were then carried out in a packed tube reactor as illustrated in Figure E-4. Experimental conditions are summarized in Table E-2. The coal residues leached represented a situation where gasification of greater than 50 percent of the coal in the seam was obtained. Since tap water was used as the leaching agent, baseline leachate analyses for all species considered except trace metals were determined. The flow rate of 1.9 cm^3/min simulated the estimated groundwater velocity in the proposed test site (1.89 cm/min). Leachate samples were collected for approximately one month and analyzed by standard procedures as specified in Standard Methods for the Examination of Water and Wastewater, American Public Health Association.

Table E-1. PROPERTIES OF COAL USED
(Dry Basis)

	Weight percent	
	Before Carbonization	After Carbonization
	Proximate	
Volatile Matter	32.91	5.41
Fixed Carbon	64.63	62.28
Ash	2.46	32.31
Sulfur	1.88	0.86
Heating value, J/g	3.4071 x 10⁷	2.2358 x 10⁷
(Btu/scf)	(14,649)	(9,613)
	Ultimate	
Carbon	80.54	61.81
Hydrogen	5.59	1.89
Nitrogen	1.76	1.01
Sulfur	1.92	0.81
Ash	2.60	32.31
Oxygen (by difference)	7.59	2.12

Source: L-8617

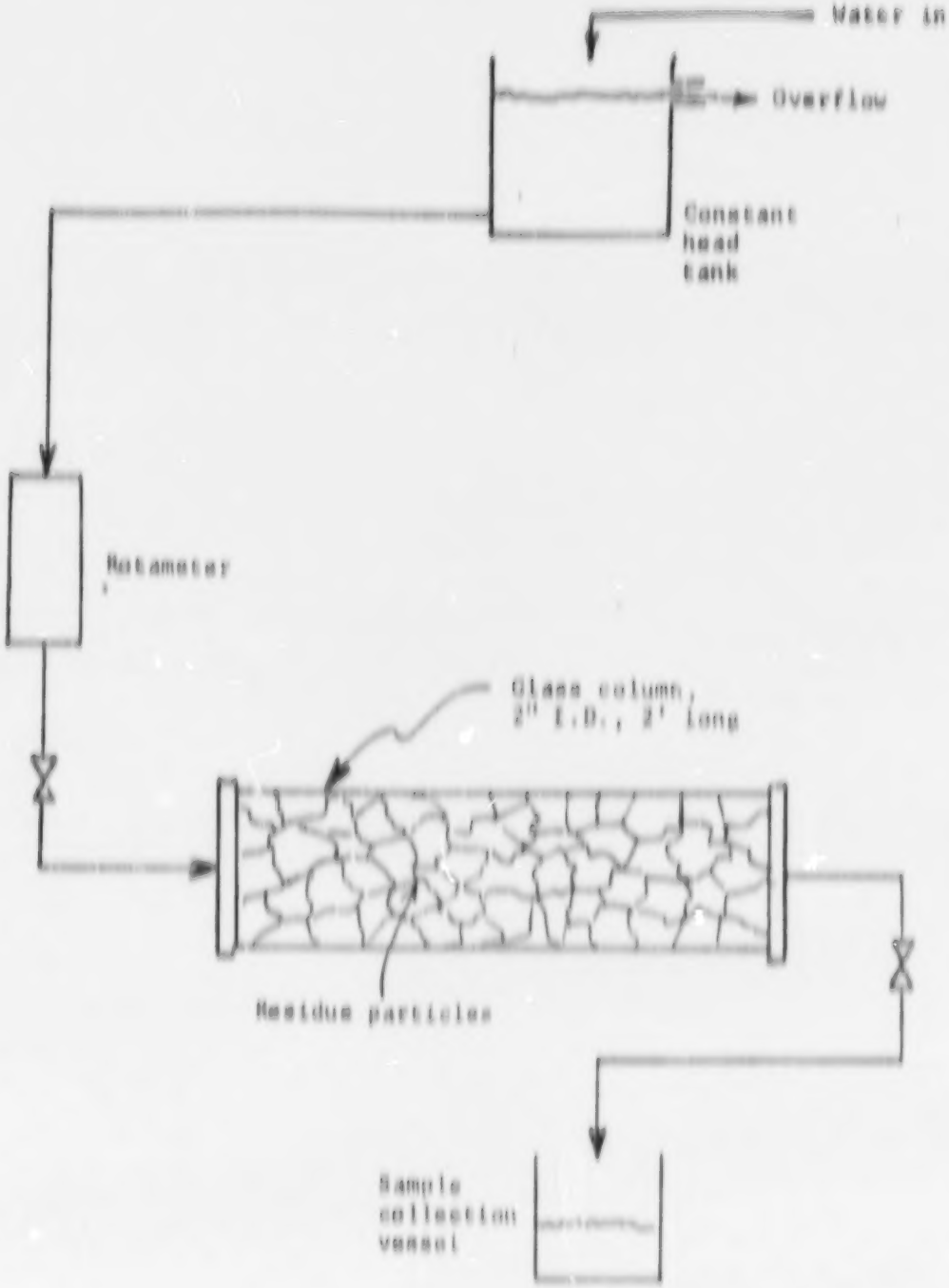


Figure E-4. LEACHING APPARATUS
(Source: L-8617)

Table E-2. EXPERIMENTAL PARAMETERS IN LABORATORY LEACHING STUDIES

Residue Particle Sizes

Particle size	Mesh size, cm (in)	Average diameter, cm (in)
Small	-25.4 + 88.9 (-10 + 35)	0.103 (0.0407)
Medium	-7.6 + 15.2 (-3 + 6)	0.500 (0.197)
Large	-2.67 + 1.88 (-1.050 + 0.742)	2.28 (0.896)

Packed Tube Properties

Particle size	Particle mass needed to fill tube (grams)	Volume of water in packed tube (ml)	Water residence time in tube (hours)	Duration of run (days)
Small	648	605	5.35	27.196
Medium	520	680	6.00	28.250
Large	446	765	6.75	31.479

Source: L-8617

Later studies will involve analysis of organic components by gas chromatography/mass spectrometry.

Results were presented graphically for some components as shown in Figures E-5 through E-9. Leaching curves were fitted by an exponential decay equation; phenols did not fit this curve, however. Decay coefficients calculated for each component are tabulated in Table E-3 along with their initial concentrations. The results were compared to available water quality standards.*

The general conclusion held to date is that no long-term problems should result from in-situ gasification processes, although in some cases, initial releases are higher than standards. These cases include COD, ammonia and phenols. Values for COD, nitrate, nitrite, sulfate and total dissolved solids were all below the levels used for comparison in this study. No standards for comparison were available for organic nitrogen or organic acids. All metal concentrations in the effluents were found to be generally lower than those in the city tap water used in the leaching experiments. It was postulated that the coal residue absorbs metal ions

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* *Promulgated and recommended standards for comparison in the referenced study include:*

BOD, COD	*Effluent averages of samples, Tuscaloosa (Alabama) Wastewater Treatment Plant.*
BOD	*Effluent monthly average set by EPA as suitable for Tuscaloosa Wastewater Treatment Plant.*
NH_3 *Nitrite* *Sulfate* *Phenols*	*Recommended maximum level for public water supply (Water Quality Criteria 1972)*
TDS	*Desirable maximum level for public water supply; may be exceeded if concentration of other individual substances remains below recommended limits (Water Quality Criteria 1972).*
Nitrate	*Maximum level set by law for public water supply (Federal Register, December 24, 1975).*

rather than emits them. Particle size of the residue was also shown to be a factor. In general both C_0 and r (initial concentration and decay constant, respectively) are larger for small particles than for large particles.

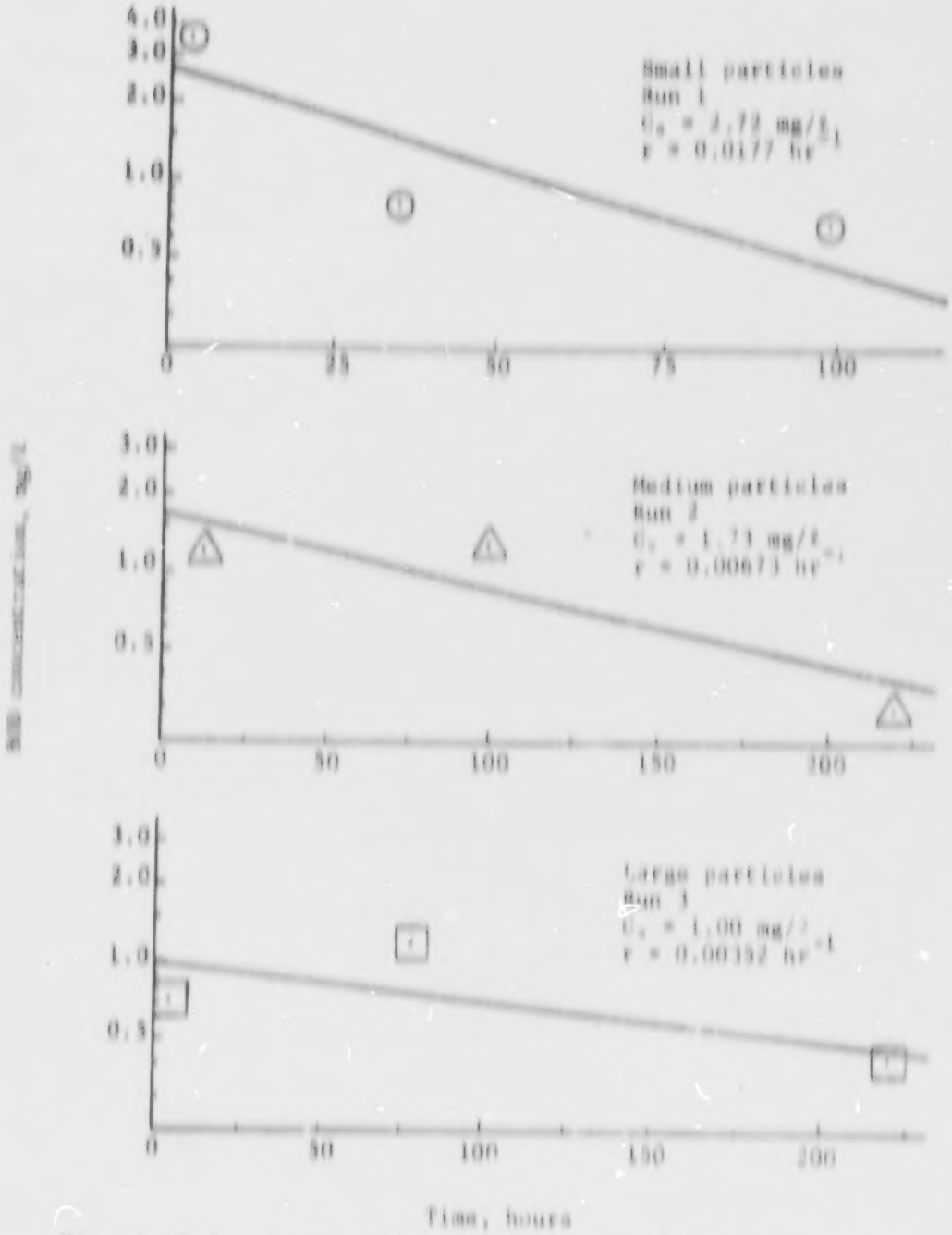

Figure E-5. BOD CONCENTRATION CHANGE WITH TIME IN THE CONTACTING EXPERIMENTS
(Source: L-8617)

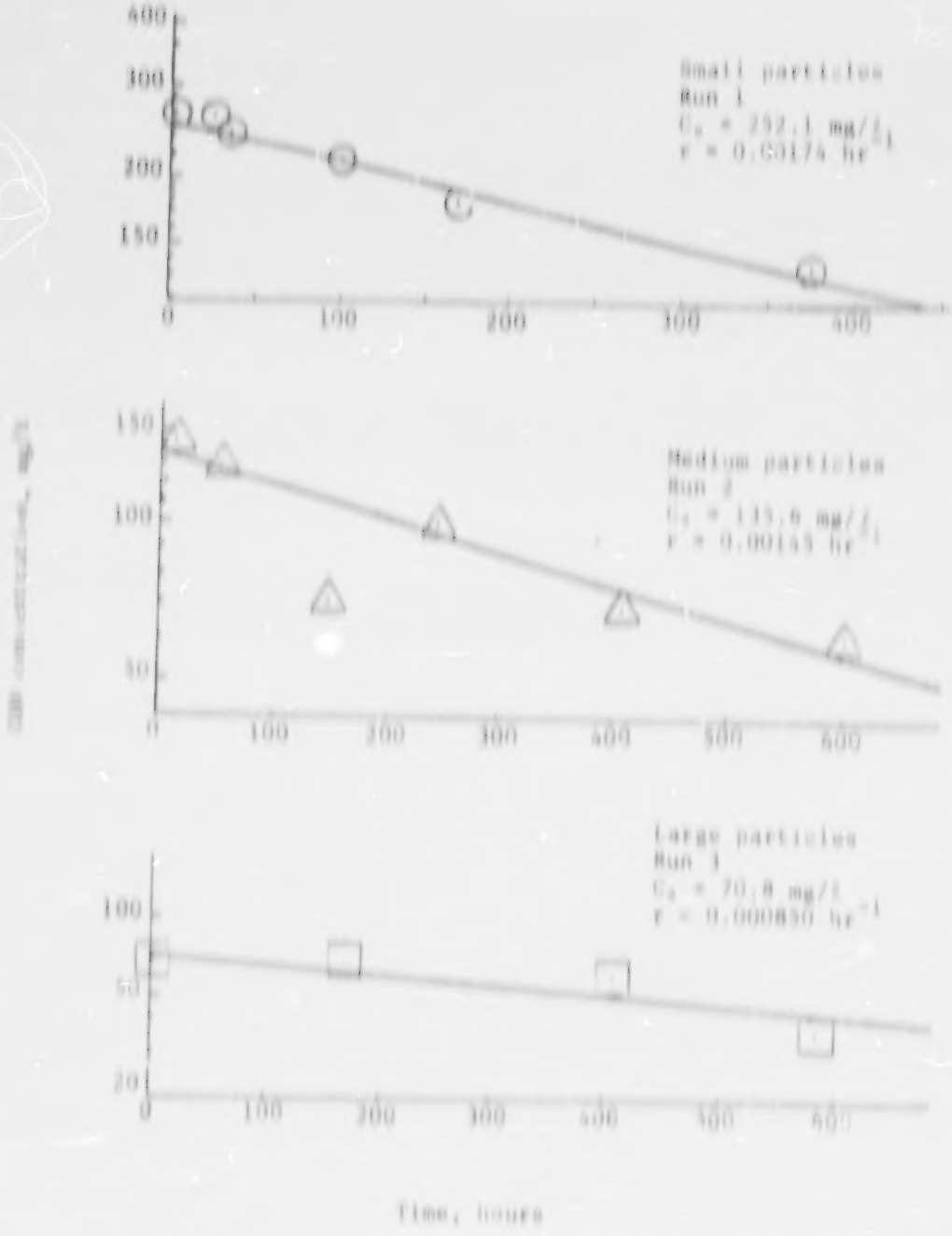

Figure E-6. COD CONCENTRATION CHANGE WITH TIME IN THE CONTACTING RUNS (Source: L-8617)

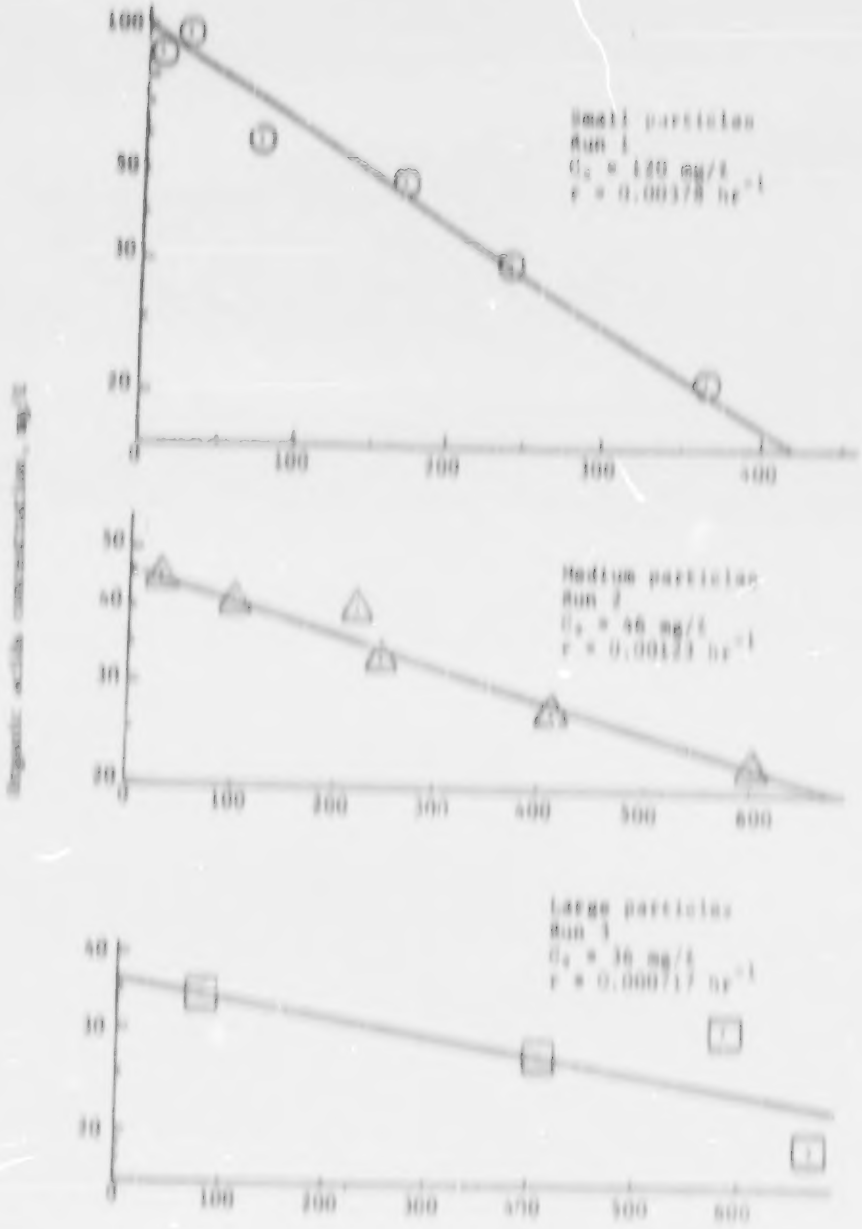

Figure E-7. ORGANIC ACIDS CONCENTRATION CHANGE WITH TIME IN THE CONTACTING RUNS (Source: L-8617)

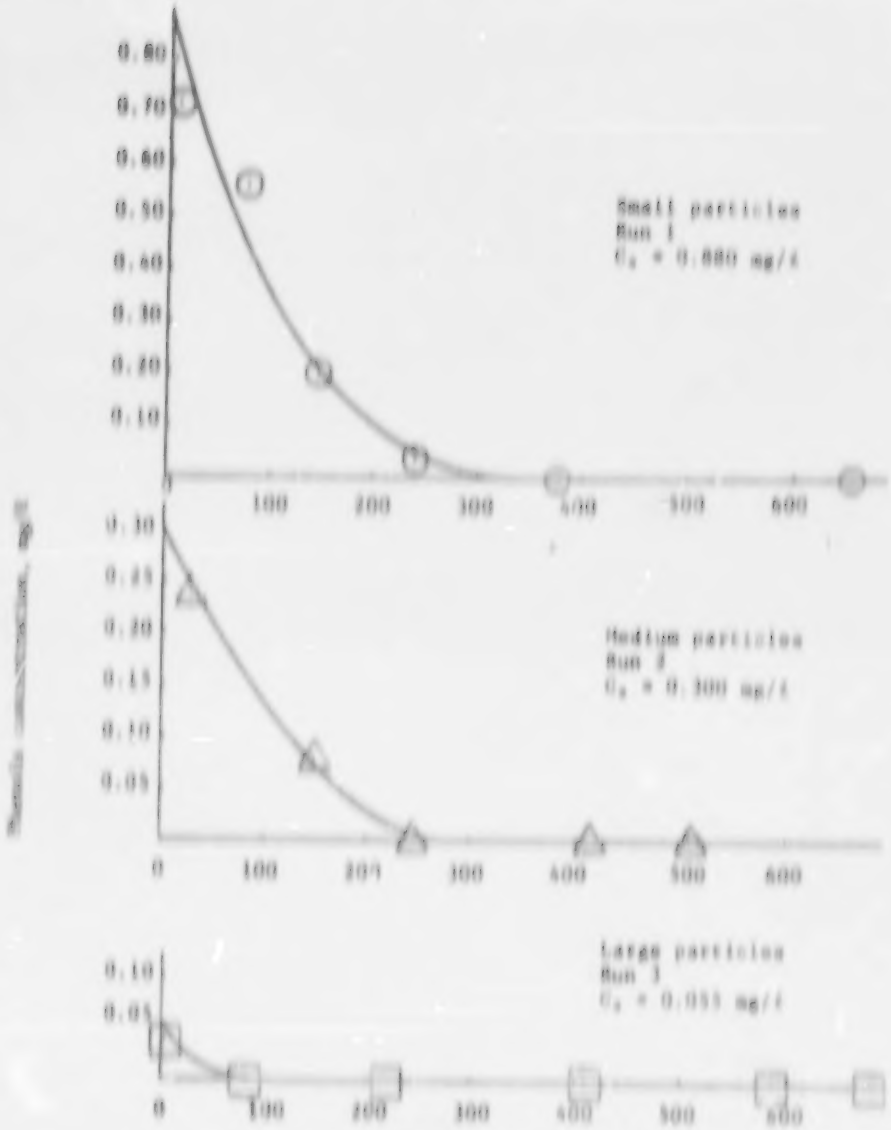

Figure E-8. PHENOLS CONCENTRATION CHANGE WITH TIME IN THE CONTACTING RUNS (Source: L-8617)

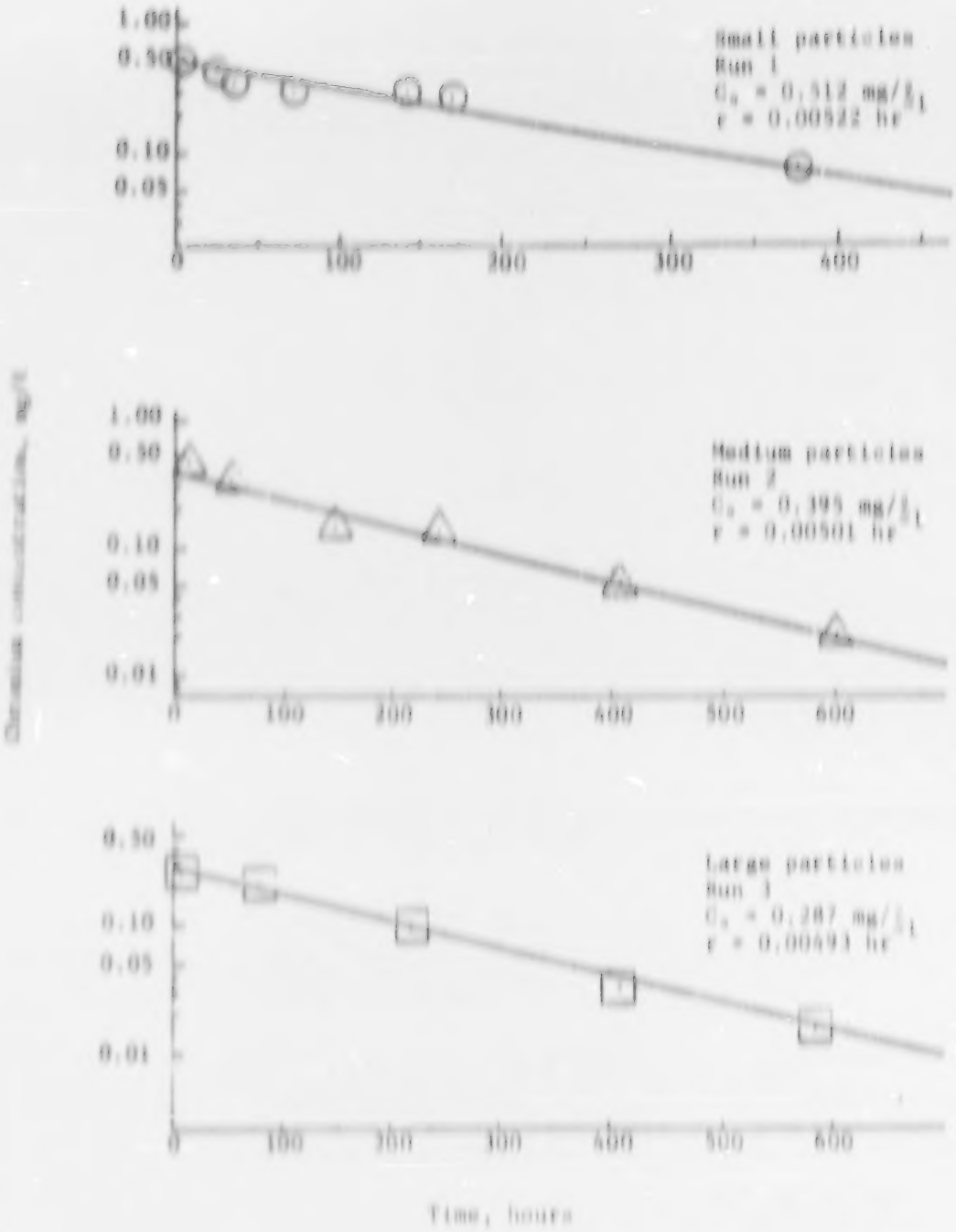

Figure E-9. CHROMIUM CONCENTRATION CHANGE WITH TIME IN THE CONTACTING RUNS (Source: L-8617)

Table E-1. WATER EFFLUENT ANALYSIS EXPONENTIAL DECAY CONSTANTS

Substance	Particle Size	C_0, mg/l	r, hr^{-1}
BOD	Small	2.72	0.0177
	Medium	1.73	0.00673
	Large	1.00	0.00352
COD	Small	252	0.00174
	Medium	136	0.00145
	Large	71	0.00085
Organic Acids	Small	120	0.00178
	Medium	46	0.00123
	Large	36	0.000717
Ammonia (N)	Small	3.49	0.00288
	Medium	3.22	0.00213
	Large	2.23	0.000817
Nitrate (N)	Small	3.8	0.000945
	Medium	3.1	0.000548
	Large	2.6	0.000457
Sulfate	Small	23.8	0.00121
	Medium	21.9	0.00113
	Large	9.2	0.000624
Organic Nitrogen	Small	2.34	0.00122
	Medium	1.65	0.000876
	Large	1.34	0.000401
TDS	Small	311	0.00516
	Medium	196	0.00251
	Large	159	0.00150
Phenol	Small	0.880	-
	Medium	0.300	-
	Large	0.055	-
Chromium	Small	0.512	0.00522
	Medium	0.395	0.00501
	Large	0.287	0.00493
Copper	Small	0.970	0.0105
	Medium	0.905	0.00667
	Large	0.748	0.00447
Manganese	Small	1.25	0.0110
	Medium	0.896	0.00632
	Large	0.741	0.00594
Sodium	Small	2.62	0.0110
	Medium	2.46	0.00632
	Large	1.99	0.00392
Nickel	Small	1.36	0.00961
	Medium	1.22	0.00810
	Large	0.403	0.00366
Zinc	Small	2.94	0.0129
	Medium	1.22	0.00830
	Large	0.756	0.00621

Source: L-8617

APPENDIX F

RANN DIVISION (NATIONAL SCIENCE FOUNDATION)/ UNIVERSITY OF TEXAS - IN-SITU CONVERSION OF TEXAS LIGNITE TO SYNTHETIC GAS

In September 1974, the University of Texas at Austin initiated a project entitled "In-Situ Conversion of Texas Lignite to Synthetic Gas." This project is being conducted under the sponsorship of the RANN (Research Applied to National Needs) program of the National Science Foundation, Texas Utilities Services Company, Continental Oil Company, Mobil Oil Corporation, and the State of Texas (L-9168, L-9169).

The objectives of this program are:

- Determine which geological, physical and chemical conditions are conducive to application of underground gasification

- Develop a mechanistic description for the dominant chemical and physical processes occurring during underground gasification (this would provide a design basis for later field testing)

- Demonstrate that in-situ gasification can be operated and controlled satisfactorily on a laboratory scale, maintaining consistent production

- Obtain engineering and geological data for several candidate in-situ gasification sites, based on core drilling at those sites

Scope of Work

To achieve the objectives of this project the following approach is being taken:

- Develop a gasification channel simulation model to facilitate an investigation of the technical feasibility of in-situ gasification

- Develop an economic computer model to facilitate a study of the economic feasibility of in-situ gasification

- Design and construct a combustion tube

- Conduct subsequent experiments in order to obtain information on pyrolysis, gasification pattern, and gasification products

- Develop mathematical models suitable for design scale-up of in-situ gasification facilities

- Use all program intermediates to develop a technical and economic basis for evaluating the potential of in-situ gasification for a given site

Experimental Configuration

To test the modeling hypothesis for an in-situ gasification system it is necessary to construct a suitable experimental apparatus, which is nearly completed. The experimental system consists of a refractory-lined, five-centimeter diameter, one-meter

long, insulated vertical stainless steel tube in which the reaction will take place. The tube will be packed with small pieces of lignite. In order to sustain sufficient flow rates, the bed will have a specified porosity. Metering systems will be installed to monitor the flow rate of oxygen and nitrogen to the reactor, and thermocouples capable of measuring temperatures up to 1100°C will be used to measure the temperature at six points in the reactor. Gas samples will be collected in evacuated sampling bottles and will be analyzed for carbon monoxide, oxygen, nitrogen, and carbon dioxide via gas chromatography. Due to the toxic nature of the effluent gas, extensive safety precautions will be taken. A flammability meter will be used to prevent any possible explosion.

Project Status and Results

Based on the work conducted during the first year of the program it has been concluded that:

- In-situ gasification is technically feasible for application to the deep-basin Texas lignite

- In-situ gasification effectively expands the extraction limits for coal by a factor of ten over strip mining; i.e., overburden to seam ratios of approximately 150:1 appear to be economic for in-situ gasification compared to 15:1 for strip mining

The purpose of the next two years' research is to develop a geological and engineering design for the application of in-situ gasification to the large deposits of deep-basin lignite.

APPENDIX G

OTHER U.S. IN-SITU GASIFICATION PROJECTS

Currently, there are several other in-situ gasification projects being conducted or recently completed in the U.S. under various sponsorships. A brief description of each of these projects follows.

Los Alamos Scientific Laboratory

This project is being developed without sponsorship so that it can be prepared as a proposal to ERDA. The primary features of this project are:

- The process is tailored for application in semi-arid regions of the Southwest
- The process will use CO_2 and O_2 instead of steam and oxygen or air as the gasifying agents

This particular gasifying technique will involve two stages. In stage 1, the coal bed is pretreated by drying with waste heat and hydraulic fracturing. Stage 2 involves gasifying the coal by using CO_2 and O_2.

Texas A & M University (L-9175)

Gasification of lignite via reverse combustion linkage and subsequent intense forward gasification between two wells is currently under study by the Petroleum Engineering Department at Texas A & M University. Initial tests are planned for two wells about 22.5 m (75 feet) apart. The gasifying agent to be used is air, producing approximately 14,155 m^3 (500,000 ft^3) of gas per day.

Sandia Laboratories (L-1436)

Sandia Laboratories is conducting a project under the sponsorship of ERDA to monitor the Hanna in-situ experiments. It is expected that the results of this work can also be applied to the high-Btu in-situ gasification project being conducted by the Lawrence Livermore Laboratory.

Argonne National Laboratory (L-8585)

This project involves the investigation of reaction-controlling variables and product distributions for the gasification of both coals and chars utilizing steam and oxygen. Included in this task is the investigation of the effects of using brackish water as the water supply. ERDA is sponsoring this program.

West Virginia University (L-1436)

The University has been awarded two contracts totalling $29,983 by the Bureau of Mines to conduct computer studies on in-situ gasification.

Project Thunderbird (L-1436)

This was a U.S. Bureau of Mines in-situ gasification feasibility study that was conducted from 1967 to 1969. Gasification of 15-m (50-ft) thick seams at a depth of 305 to 670 m (1000-2200 ft) was the primary concern of this study. These thick seams are considered uneconomical to mine.

A. D. Little Study (L-1436)

In 1972 A.D. Little reviewed available information in order to evaluate the technical feasibility of in-situ gasification of coal. A report based on the findings was published

APPENDIX H

UCG PROJECTS OUTSIDE THE U.S.

The bulk of the work done outside the U.S. has been conducted in the U.S.S.R. where underground coal gasification has been under investigation since the 1930's. There are currently four or five electricity generating stations powered by gas produced underground. Russian technology has been reviewed in a report prepared by the Lawrence Livermore Laboratory under contract to ERDA (L-8618). This document should be consulted for information on Russian in-situ projects.

A three-year cooperative study between Belgium and West Germany was recently announced (L-9176). The objective of this work is to develop in-situ technology for utilization of the vast coal resources located in the West German Ruhr region through northern Belgium and the Netherlands. Initial tests involving air combustion will probably get underway sometime in early 1978. Air at pressures ranging from 20 to 50 atm will be injected into coal seams about 1000 m deep. The anticipated heating value of the product gas is between 100 and 140 Btu/scf. Application in a combined-cycle system is being considered in order to obtain the maximum energy usage efficiency. If the results are encouraging, experiments substituting hydrogen for air may be attempted.

In Canada the governments of Alberta and British Columbia are studying the feasibility of developing projects within their provinces (L-1436). A test burn has been conducted but no details are readily available at this time.

In the United Kingdom, the National Coal Board and the C.E.G.B. (Central Electricity Generating Board) are also sponsoring an evaluation of UCG. Pilot-scale trials in a 5-MW plant at the Newman Spinney Station near Sheffield have been underway

since 1957 (L-1436, L-8605, L-9176). A low-grade coal with high mineral content is being gasified here.

Gasification of brown coal in northern Bohemia, Czechoslovakia, has been under investigation since 1956. Following several trial tests, plans were reported for application of the basic technology (lateral gas removal) to an industrial-scale project possibly in conjunction with a 220-MW power generating unit. Purification of the crude gas involves tar and H_2S removal. Wastewater treatment includes NH_3 removal, phenol treatment by butyl acetylate, and biological purification (L-4858, L-4860).

One of the aspects of UCG under study in Poland includes control of roof behavior. Technologies involving air versus oxygen blast have also been evaluated with respect to their effects on void filling and roof control (L-9048).

Other UCG projects are currently underway in Germany, France (Morroco), and other European countries. In addition, Japanese literature published in the 1960's describes laboratory studies of spontaneous combustion and underground gasification of coal (L-5715, L-5718, L-8603, L-8604). A planned on-site test at Sumitomo Coal Mining Co., Ltd., at Akadaira of Hokkaido was described.

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